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PELLETIZED VS. NATURAL IRON ORE TECHNOLOGY ENERGY, LABOR, AND CAPITAL CHANGES

by

Peter Kakela

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ENERGY, LABOR, AND CAPITAL CHANGES

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ABSTRACT

Resource gathering has depended upon leaner and leaner crude ores in recent years. Iron ore mining typifies this trend. A major shift from high grade natural iron ore to pelletized lean iron ore has occurred since 1955. Steel made from these iron ores is the most important resource to the U.S. economy and to the nation's energy consumption.

Total energy requirements per ton of iron-in-ore for natural and pelletized ore were calculated by a hybrid energy analysis. (Total energy includes the direct and indirect energy of fuels and the embodied energy of materials consumed.) Energy requirements for ore preparation were subsequently considered as one energy input (embodied) to blast furnaces. Total energy requirements per ton molten iron were calculated for each year from 1955 through 1975 to identify changes attributable to the shift in iron ore preparation.

Four results were found. (1) In practice, the lean ores are energetically superior. Pelletized ore requires more energy at the mine than natural ore, but pellets produce offsetting energy savings in the blast furnace. Free thermodynamic energy of the lean taconite ores is released when pellets are formed, but more important to energy conservation is the greatly improved permeability pellets contribute to blast furnace burdens and the resulting improved chemical efficiency of blast furnace reactions. Thus, the total energy trend per ton of molten iron decreased during the period of major pellet (and other agglomerate) introduction (1955-63). Since 1963, the total energy trend has stabilized at approximately 23.5 million Btu/net ton molten iron. Although agglomerate charge continued to increase gradually, other blast furnace practices, especially the injection of supplemental fuels, nullified further energy savings after 1963. (2) Labor changes followed a similar pattern: man-hours per ton of molten iron increased at the mine with pelletization, but decreased at the blast furnace. Net labor required per ton of molten iron has decreased with pelletization. (3) Capital investments per ton of molten iron have increased greatly at iron ore mines with pelletization and decreased moderately at blast furnaces. New capital investment per ton of molten iron has increased with pelletization. (4) In the iron and steel industry, relatively low-priced energy held a substantial advantage over high priced labor between 1950 and 1969. The industry, however, discovered that capital investments in pellet plants could save both labor and energy up to 1963; after 1963 capital and energy were substituted for labor. A sharp reversal of substitutional advantage occurred in 1970; energy jumped to the most costly factor. Thus capital presently shows a strong substitutional advantage over high-priced energy and intermediately-priced labor.

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1. INTRODUCTION AND METHODOLOGY

Introduction

"Mining, beyond question, is the world's basic industry. Without it, civilization would perish."[1] Modern society is like an inverted pyramid that is precariously balanced on its mineral industry apex. In winning ore from the earth, the miner supports all subsequent industries that, step by upside step, add value to the original ores. Such is the pivotal position of the mining industry in modern civilization according to Christian F. Beukema, Vice President and General Manager of Raw Materials and Lake Shipping, United States Steel Corporation. The image is most appropriate to iron ore for this mineral industry gives birth to iron and steelmaking which in turn supplies materials for the voluminous ferrous products which are the commonplace of daily life.

The winning of iron ore from the earth requires energy, materials, labor and capital operating through technology. These requirements are figuratively embodied in the iron ore and, with passage up the subsequent steps of the metaphoric pyramid, the initial requirements are expanded at each process step. The embodied requirements of iron ore are small per unit, but they are the basis to which all subsequent processing of iron and steel products is added. Therefore, starting at the apex is a reasonable beginning to assess changes in the energy, materials, labor and capital required for iron and steel production.

This study analyzes recent technological changes in iron ore preparation (pelletization) to discover quantitative changes this technology has caused in the factors of production. Energy, labor and capital changes are measured. Materials consumed in iron ore production (e.g., wear parts, binder clays, rubber tires) are converted to the energy equivalents required for their production and delivery to point of use. In this way, materials consumed become part of the total energy requirement of iron ore production. The boundaries of analysis extend from iron ore in the ground to the molten iron product of the blast furnace (commonly called "hot metal" or, if cooled, "pig iron"). Within this system, two different iron ore preparation technologies, pelletization of ore and natural ore concentration, are considered. The effects of changing to iron ore pelletization are traced up the production pyramid to a stage in which the differences in mineral extraction technology vanish. At this point the two forms of prepared ore can no longer be distinguished. This point of indistinction for the two iron ore technologies is molten iron. That is, the physical characteristics of molten iron are the same whether pellets or natural iron ore feed the blast furnace.[2]

Pelletized iron ore was commercially introduced to the world market in 1955. Today more than 80% of the iron ore burden in the United States' blast furnaces is pelletized (or otherwise agglomerated) iron ore. Pelletized and agglomerated ores require more energy, more labor and more capital to prepare than natural ore concentrates. The pelletization technology, however, has allowed the lower grade taconite and hemitite iron ore bodies to be beneficiated into a superior blast furnace feed.

Energy aspects of the changes in iron ore preparation technology are important for several reasons: (1) the direct energy of fuels is essential to the making of steel from iron ore for the mechanical and chemical work that fuels perform, (2) energy units of measure provide a common basis for evaluating both fuels and materials consumed in the production process, (3) energy units, being a physical measure, are consistent over time and not subject to the measurement problems of inflating dollars, and (4) energy use by the steel industry is of significant magnitude to warrant special attention at a time of repeating energy crises. The steel industry consumed some 3.8 quadrillion Btu in 1973,[3] or 14% of the energy consumed by all United States industries. This represents 5.1% of the total United States energy consumption.[4] The physical and chemical changes that occur in the production process with use of pelletized iron ore cause changes in energy requirements. Analysis of these energy changes is of primary methodological importance, therefore, because it specifies the point of indistinction for the other factors of production; labor and capital. The present study, therefore, stresses energy changes attributable to pelletization.

Methodology

This study calculates total energy requirements for natural iron ore concentrates and for pelletized iron ore. The method has been to acquire from mining operators physical measures of fuels and materials consumed in the two iron ore preparation processes. Plant visitations and personal interviews were conducted throughout a wide spectrum of the steel-making industry. In addition, personal interviews were conducted with industrial experts in pelletized ore, natural ore, scrap iron and steel, electric steel mills and integrated steel mills to assess energy requirements associated with the change to pelletization. Detailed energy and material inventory forms were completed by four natural ore operators and six pelletization operators. Raw data from a Minnesota Energy Agency inventory of capital and labor factors were also used. Industry wide averages were obtained from various trade associations and state and federal agencies. Other publications, especially from contract research laboratories and university researchers, were used where primary data were lacking. Finally, calculations were compared to values predicted by the energy input-output model developed by the Center for Advanced Computation, University of Illinois, Urbana-Champaign.[5] Fuels and materials data were converted to Btu equivalents according to the energy conversion factors presented in Table A-1 of the Appendix. Direct energy conversion factors for fuels are available from numerous sources. These have been expanded in Table A-1 to include the indirect "energy intensities" required to provide fuels (e.g., coal mining, petroleum exploration and refining, natural gas distribution, electricity generation) as determined by the CAC energy input-output model. Embodied energy equivalents presented in Table A-1 have been derived from published process analyses or from the energy I/O model.

This study is a hybrid analysis of one technology within an industrial process.[6] The technological conversion to pelletized iron ore has occurred since 1955 in concert with other changes, and it caused direct repercussions in two distinct Bureau of Economic Analysis (BEA) sectors. For these reasons, straight energy I/O analysis would not provide accurate enough measurements of the changing energy relationship associated with the transition to pelletization.

The shortcoming of a hybrid analysis, however, is that not all indirect and embodied energy requirements can be identified. At some point, pursuit of the energy links must be stopped. For example, the energy required to explore the Mesabi Range for the ore body now being mined to produce natural ore concentrates and pelletized ore has not been inventoried in this study. Although this exploration represents an indirect energy requirement to the ore preparation process, its tiny magnitude and obscure nature make it impractical to assess specifically. In general, as processes become more removed from the specific activity being analyzed, their energy requirements decrease in proportion to total energy required. Also, the reliability for assessing energy requirements decreases as process steps become more removed from the central activity being analyzed. Therefore, in any hybrid analysis the pursuit of indirect and embodied energy requirements must be truncated at some point. Truncation is inevitably a judgment decision on the part of the researcher; i.e., the researcher must decide what is practical. The energy calculation tables show the specific points of truncation in this study.

One of the strengths of the energy I/O model is that it overcomes the truncation problem. The I/O model gathers hundreds of small and individually insignificant inputs into a significant whole. Because all inter-industry transactions are included in the I/O model, the total (direct, indirect and embodied), energy requirements of various activities can be specified. Limitations do arise, however, with the generalities of the BEA sectors, with inaccuracies in deflating current dollars to 1967 dollars and with adjusting for producer prices For the present study, a combined or hybrid analysis was selected because the pelletization technology was introduced over a time span and because this technology affects more than one industrial sector. Hybrid analysis combines both process analysis and Input/Output analysis.

The overall scope of the present study has two phases. First, total energy requirements are calculated separately for natural iron ore concentrates and pelletized ore. These calculations follow the hybrid analysis method and employ original data received from numerous natural ore and pellet plant operators located in the upper Great Lakes region. As a result of this analysis, an embodied energy value per ton of contained iron is calculated for both natural ore concentrates and pellets. The second phase of this study focuses upon changes that have occurred in blast furnace operation as a result of the shift to pelletized iron ore burdens. The increase in embodied energy inherent in pelletized iron ore production is therefore added to other energy requirements to derive a <u>total energy trend</u> per ton of molten iron for 1955 through 1975. The total energy trend is the change in total energy requirements over time. Changes in energy requirements attributable to pelletized ore burdens can be identified from the trend.

In addition to the total energy trend of molten iron, changes in labor and capital requirements resulting from pelletized ore burdens are calculated.

<u>Why Pellets</u>?

Repercussions of the change to pelletized iron ore may be more clearly perceived if the reasons for conversion to this technology are understood. The knowledge fundamental to pelletizing low-grade magnetic iron ores was developed and widely disseminated some 60 years ago (i.e., more than 30 years before pelletization came into commercial use). Passage of the first taconite tax law in Minnesota, a significant political and financial action favoring pelletization, occurred in 1941. Private financial commitments, however, were not made until much later.

Following World War II there was a perceived scarcity of high grade natural iron ore. The iron and steel industry's response to this scarcity was twofold: (1) a worldwide search for more natural ore deposits was launched, and (2) the development of commercial scale pelletization technology was accelerated. Thus, geologic and technologic solutions were sought to the shortage of iron ore. In the ensuing years, both ventures proved successful.

At the same time that efforts were being made to overcome the iron ore shortage, other technologic developments were occurring in steelmaking that paved the way for pelletization; the basic oxygen furnace (BOF) is an especially important factor. Developed in Austria in 1949, the BOF converted molten iron from the blast furnace into quality controlled steel much faster and cheaper than the widely used open-hearth (O-H) furnaces. BOFs began to replace O-Hs with remarkable speed. In 1955, O-Hs accounted for nearly 90% of raw steel production in the United States; by 1970 this percentage had fallen to less than 30%. Meanwhile, BOF production rose from near 0% in 1955 to almost 50% in 1970. The inertia of major capital expenditures in the steelmaking industry led one analyst to predict as early as 1965 that "it appeared unlikely that any new open-hearth furnaces would ever be build again."[7]

The benefits of the BOF are compelling. First, BOFs are cheaper to operate than O-Hs. According to a 1964 United Nations study, total cost savings for BOEs were more than 12%, when compared with O-Hs, per ton of steel produced.[8] Labor, capital and other conversion costs were all lower for the BOF. Only material costs increased with BOFs, and this resulted from increased molten iron requirements. The BOF is faster as well as cheaper. It takes about 40 minutes to complete a steel furnace cycle (a "heat") in the BOF, whereas the O-H requires at least eight hours in its accelerated state and often up to twelve hours under traditional operation.

However, BOFs require a larger quantity, and a more consistent supply, of molten iron than the old O-Hs. The reasons for this increased requirement are twofold. First, the BOF normally has a charge of 72% molten iron and 28% scrap iron and steel.[9] The O-H charge averaged 50% or less molten iron, with scrap often making up the majority of the charge. Second, the BOF requires a much more consistent supply of molten iron because its charge cannot vary from the 72%:28% ratio very much without significant capital and technologic modifications. In contrast, the extreme flexibility of the O-H can accommodate charges ranging from near zero up to a 100% scrap, depending upon scrap availability. Common charge ratios vary from 30%:70% to 70%:30% molten iron to scrap in the O-H. Conversion to BOFs, therefore, demanded a larger volume of molten iron and a more consistent supply.

As commercial scale pelletization of iron ore technology progressed, associated benefits were discovered that made this solution to the iron ore shortage most attractive in its own right, but pellets took on even greater significance in light of the BOF demands for molten iron. Pelletized iron ore burdens were found to increase the rate of molten iron production for a given blast furnace. Pellets also reduced coke costs.

Therefore, pelletized iron ore could guarantee the increased quantity of molten iron demanded by the BOFs even with existing blast furnaces. Pelletized ore burdens allow 50% to 100% more molten iron productivity from a given blast furnace with relatively minor capital modifications.

The first commercial scale pellet plant was constructed by Reserve Mining Company at Silver Bay, Minnesota, and began shipping in 1955. By 1965, the pellet capacity of the United States had reached 32 million tons and the capacity in Canada was 16 million additional tons. Another 25 million additional tons of pellet capacity was under construction or firmly planned in North America at that time. Therefore, once made, the commitment to pellets was strong and the United States led the world.

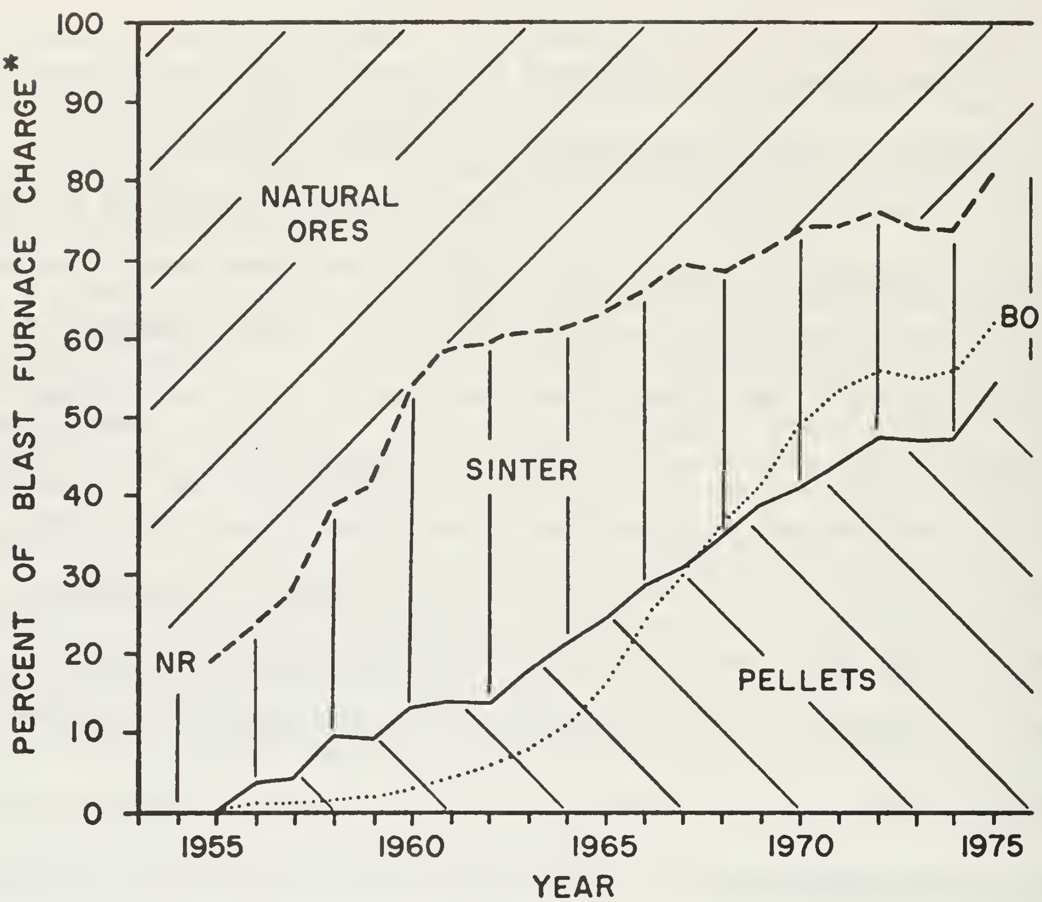
Thus, both pelletization and BOF technologies, from first commercialization in mid 1950 to dominance of their respective steelmaking sectors by 1970, have been a coupled diffusion process of spectacular speed in an industry that has appeared to be traditionally deliberate. (See Figure 1.)

2. IRON ORE PREPARATION

Introduction

The nature of the ore body greatly influences the beneficiation processes employed. Nonmagnetic hemitite iron ores are the primary source of natural ore concentrates, whereas magnetic taconite is the primary source of pelletized ores.

From the late 1800s through the 1950s, direct shipping natural ores comprised the majority of iron ore produced in U.S. mines. (See Figure 2.) Direct shipping ores are considered untreated; they may be shipped as they come from the mine (crude ore) if they are of particularly high quality and desirable size, or they may be subject to primary crushing and in some cases screened for size.[10] For many years, the rich iron ore deposits of the Upper Great Lakes supplied vast amounts



*BOF LINE IS % OF STEELMAKING FURNACES

——— % PELLETS OF B.F. CHARGE

– – – % TOTAL AGGLOMERATES

·········· % BOF STEEL FURNACES

NR – "NOT RECORDED" EARLIER BY AISI

Figure 1. Concurrent Introduction of Pelletized Iron Ore Charge to Blast Furnace and Conversion to BOF Steel Furnaces.

DATA SOURCE: AISI.

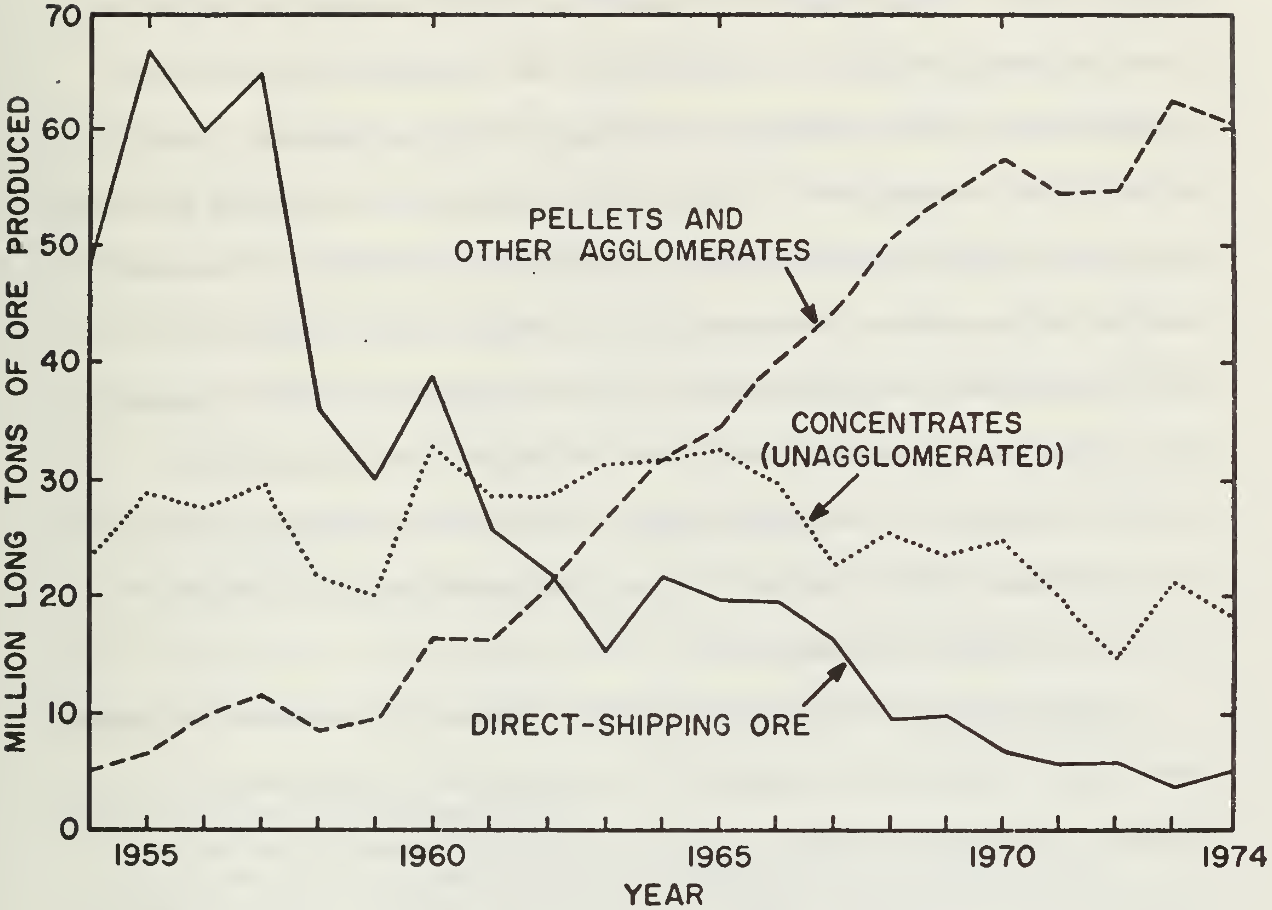


Figure 2. U. S. Mine Production of Iron Ore by Type, 1954 to 1974.

DATA SOURCE: U.S. Bureau of Mines.

of high quality direct shipping ore that met the needs of U.S. blast furnaces. From the mid-1950s, the role of direct shipping ore has been reduced. Two of the causes of this reduction are (1) a rise in blast furnace burden quality standards and (2) a decline in quality of crude ores mined from U.S. iron ranges. As a result, most crude ore is now treated before shipping. Treatment includes washing, jigging, high-density separation (or heavy media separation), spiraling and other gravity processes, scrubbing and some magnetic processes. Treatment results in natural ore concentrates, a category which includes all beneficiated ores not agglomerated before shipment to blast furnaces. [11] Together, direct shipping ores and natural ore concentrates are here referred to as natural ores. Since direct shipping ores are rarely produced today, natural ore concentrates comprise virtually all U.S. natural ore production.

Pelletization of iron ore requires a number of treatment processes; some can be similar to treatments for natural ore concentrates, but pellets require considerably more treatment and several distinctive steps. The ore commonly mined for pellets is magnetic taconite which is low in iron content (generally between 20% and 30% Fe), but is concentrated through mechanical and magnetic processes to more than 60% Fe. Treatment includes fine and coarse crushing, grinding with steel rods and balls or by autogenous processes, magnetic separation, high-density (heavy medium) separation, and other gravity separation processes. The resulting concentrated ore is of face powder consistency. It is mixed with a clay binder, rolled into marble-size balls, and indurated in kilns at approximately 2400° F.

The relatively uniform and hard iron ore pellets are then shipped to blast furnaces. Pelletization is a vast expansion of ore preparation processing at the mine-site and represents a shift of manufacturing activity from the blast furnace to the iron ore mine.

Sintering, on the other hand, is a method of agglomerating iron ore fines at the blast furnace. Sintering utilizes either fine natural ore concentrates as they are received at the blast furnace, or by-products of the blast furnace and other steel mill operations. Such by-products as flue dust, sludge, coke breeze, mill scale, cinder, and slag are combined with ore fines, ore concentrates, pulverized coal, limestone, dolomite and other materials. This mixture is ignited just long enough to fuse the various materials into a cake. It is then quenched and broken into irregular, clinker-like chunks for blast furnace feed. Both pellets made at the mine and sinter fused at the steelmill are here referred to as agglomerated ore.

Energy Required for Natural Ores

Total energy requirements for the preparation of natural ores are based upon interviews with mine operators and detailed inventories from four natural ore mines. These data represent current (1975 or 1976) practices. Each property produced less than one million tons of natural ore concentrates in the inventories year and the iron content of produced ore ranged from just over 50% Fe Natural to just over 55%. Recovery rates varied from 23% to 70%.

Total energy requirements vary for the different properties. This variance stems from the nature of the ore body being mined as much as from management practices, scale of operations and other factors. For example, the property that had the highest Btu/Ton Fe requirement was mining very deep in a pit and expended much energy (as well as other costs) to remove non-ore bearing rock and to pump water out of the pit. At the close of the inventoried year, this operation ceased. On the other hand, an engineer for the property with the lowest Btu/T.Fe case said, in reviewing his data, that the inventoried year was "a very good year" for his company.

Calculated total energy requirements for the highest case of natural ore concentrate are 59% greater than for the lowest case. The overall average based upon the arithmetic mean of individual totals for properties inventoried is 1.882 million Btu/net ton Fe delivered to U.S. blast furnaces.

The differences in inventory detail represent differences in processes and equipment employed and differences in accounting systems relied upon to compile the data. As a result of the different accounting systems, the indirect and embodied energy requirements for materials consumed was incomplete on various inventory forms. Further discussions with operators resolved some points, but unrecorded consumptions appeared to remain. This is the truncation problem in raw data collection. To reduce some of the underestimation of indirect and embodied energy requirements, a hypothetical "standard" natural ore concentrate case was constructed through the insights gained by analyzing the energy inventory forms for all mining operations. Table 1 presents these data. Figures for the process steps of the standard case are either averages for that process step derived from several energy inventories or are based upon unique data identified from one mine, but judged to be of general application.

Table 1.

ENERGY REQUIREMENTS FOR NATURAL ORE CONCENTRATES*

Process	Units/net T.Fe	Btu/net T.Fe		
Stripping Non-Ore Overburden				
Electricity	1.78 kwh	23,000		
Diesel Oil	.31 gal.	52,500	4.7%	
Explosives	.31 lb.	9,200		
Rubber tires	$ .15	6,000		
				90,700
Mining Crude Ore				
Elec. (process)	10.19 kwh	132,000		
Elec. (pumping)	6.18 kwh	80,000		
Diesel Oil	.69 gal.	115,000		
Lubricants	.10 gal.	17,000	21.4%	
Gasoline	.03 gal.	5,200		
Explosives	.89 lb.	26,600		
Rubber tires	$ .34	13,800		
Steel wear parts	$ .52	25,000		
				414,600
Concentrating Ore: fines and coarse				
Electricity	8.08 kwh	104,600		
Diesel Oil	.02 gal.	2,900		
Lubricants	.01 gal.	2,600	6.1%	
Plant repairs	$ .07	2,200		
Steel wear parts	$ .11	5,400		
				117,700
Other: e.g. office, stockpile				
Electricity	.01 kwh	150		
Diesel Oil	.08 gal.	14,000	1.1%	
Rubber tires	$ .02	1,000		
Trade margins	$ .24	6,300		
				21,450
Transportation to B.F.				
Rail (100 mi.)	210 m.t. mi. Fe	104,800		
Water (900 mi.)	1881 m.t. mi. Fe	1,185,200	66.7%	
				1,290,000
TOTAL		1,934,450	100.0%	

*Hypothetical "standard" case constructed from actual mines inventoried.

Total energy required to produce and deliver one ton Fe of natural ore concentrates to U.S. blast furnaces in the standard case is 1.934 million Btu. Energy required to transport these natural ores to blast furnaces accounts for two-thirds of the total. Disregarding transportation and only considering mine-site preparation of natural ores, energy required to mine crude ore far exceeds other operations, including ore concentrating. One item, electricity for pumping water to keep the pit dry enough for continued mining, accounts for a surprising proportion (more than 12%) of the energy required to prepare natural ores. In general, the preparation of natural ores relies primarily on electrical power and secondarily on diesel oil.

Indirect energy accounts for over 60% of the total energy required for natural ore preparation. If the mine operator, therefore, were to view the energy required to produce natural ore in terms of the heat value contained in the fuels and electric power consumed on site, s/he would see less than two-fifths of the total energy requirements.

Recent trends suggest that measurements of energy required for current natural ore concentration may be higher than the average energy requirement over the time interval of 1955 to 1975. For example, the shipped percentage for concentrate mines inventoried ran close to the "51.50% Fe Natural" base price level. To reach this level, some operators had a crude ore to produced ore ratio in excess of 4:1. In previous years the Fe percentage of natural ore concentrates was higher and the ratio of crude ore to shipped ore was lower. These factors and others suggest that energy requirements for natural ores per ton Fe shipped have risen to their present levels since the early 1950s.

Energy Requirements for Pelletized Iron Ore

Data received from six pelletizing plants were analyzed. These data again apply to current practices (1975-1976). Annual productions for the inventoried year ranged from less than one million tons to over 10 million tons of pellets produced. Fe percentages varied from just over 60% to over 65%. Considering only those operations mining magnetic taconite and using energy requirements for transportation from Minnesota's Mesabi Range as standard, an arithmetic mean total energy requirements was calculated to be 4.941 million Btu/net ton Fe delivered to U.S. blast furnaces.

Pellet plants have less variation in total energy than natural ore mines. The largest energy requirement for pellets is only 12% greater than the least given the standardizing assumption stated above. Part of the reason for less relative variance is that total energy requirements for pellets are much larger than for natural ores. Pellets require more than two and one-half times as much energy for preparation and delivery to blast furnaces than do natural ores.

Differences in total energy required per ton Fe for different pellet plants are caused primarily by two factors: (1) the age of the plant, and (2) the nature of the ore body mined. In the first case, newer plants and larger plants generally require less total energy per ton of pelletized Fe.* Regarding the ore body, nonmagnetic ores require substantially more energy to beneficiate than magnetic taconites. Comparing individual mines, I calculate total energy at the mine-site of nonmagnetic pellet plants to be 45% greater than the average and 57% greater than the most efficient magnetic taconite pellet plants.[12] Also, harder ore requires slightly more energy for crushing and grinding.**

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*An exception may be the coal fired kilns which are being introduced presently at several plants.

**Nonmagnetic hemitites occur throughout the upper Great Lakes iron ranges, but are only being pelletized in portions of northern Michigan where magnetic taconites are not available. Magnetic taconites on Minnesota's Mesabi Range tend to increase in hardness from west to east.

TABLE 2.

ENERGY REQUIREMENTS FOR PELLETIZED ORE*

Process	Units/net T.Fe	Btu/net T.Fe	
Crude Ore Mining			
Electricity	3.67 kwh	47,600	
Natural Gas	10.07 c.f.	11,100	
Diesel Oil	.66 gal.	111,000	
Gascline	.02 gal.	3,590	
Lubricants	.03 gal.	6,010	6.6%
Explosives	3.93 lb.	118,000	
Oxygen	109.29 c.f.	20,000	
Rubber tires	$ .30	12,100	
Steel wear parts	$ .08	3,700	
Calcium chloride	$ .04	7,470	
			340,570
Coarse Crushing			
Electricity	3.55 kwh	46,000	
Fuel Oil + nat. gas (heat)	.08 gal. oil eq.	13,400	
Lubricants	.01 gal.	1,040	1.4%
Steel wear parts	$ .11	5,120	
Chemicals	$ .02	4,230	
			69,790
Fine Crushing			
Electricity	8.49 kwh	110,000	
Lubricants	.00 gal.	500	2.4%
Steel wear parts	$ .28	13,300	
			123,800
Concentrating			
Electricity	94.03 kwh	1,218,000	
Natural Gas	120.69 c.f.	133,000	
Nat. gas (heat)	77.13 c.f.	85,000	30.7%
Lubricants	.00 gal.	700	
Rod, balls, liners	8.86 lb.	155,000	
			1,591,700
Water Handling & Tailings			
Electricity	14.28 kwh	185,000	
Additives	$ .02	4,470	3.7%
			189,470
Agglomerating & Induration			
Electricity	39.60 kwh	513,000	
Natural Gas	994.56 c.f.	1,096,000	
Gasoline	.00 gal.	225	
Lubricants	.02 gal.	4,000	31.9%
Bentonite	34.00 lb.	20,400	
Steel wear parts	$ .06	2,940	
Neutralizers	$ .05	9,200	
Refractories	$ .07	7,930	
			1,653,695
Others: eg. office, shop.			
Electricity	1.34 kwh	17,300	
Natural Gas	11.80 c.f.	13,000	
Propane	.11 lb.	2,800	
Diesel-fuel oil	.24 gal.	40,000	2.2%
Lubricants	.01 gal.	2,500	

*Hypothetical "standard" case constructed from actual mines inventoried and assuming magnetic taconite ore mined at a northern Minnesota location.

Process	Units/net T.Fe.	Btu/net T.Fe	
Trade Margins	$ .148	3,900	
			79,500
Loading Pellets			
Electricity	.74 kwh	9,620	
Diesel oil	.02 gal.	3,730	
Gasoline	.01 gal.	900	0.3%
Lubricants	.00 gal.	200	
			14,450
Transport to B.F.			
Rail (100 mi.)	177 m.t. mi. Fe	88,400	
Water (900 mi.)	1590 m.t. mi. Fe	1,002,000	21.0%
			1,090,400
TOTAL		5,153,375	100.0%

Thus, depending upon age of plant and the ore body mined, different pelletizing processes are practiced with some variance in total energy required per ton of Fe in pellets.

Because the energy inventory data collected show variations in the pelletizing process, a hypothetical "standard" pelletized ore case was developed. This standard is presented in Table 2 and represents total energy requirement calculated for magnetic taconite shipped from a northern Minnesota location. Total energy required in the standard pelletization case is 5.153 million Btu/net ton Fe delivered to U.S. blast furnaces.

The transport of pellets requires a smaller relative proportion of total energy than does natural ore transportation. Pellets also require slightly less actual energy (in Btu/ton Fe) to transport because they are higher in iron content (about 63% Fe) than natural ores (about 53% Fe). Thus there is 10% less waste rock transported with pellets. In preparing pellets, two processes require most of the energy, but use different fuels. Concentration of ore depends primarily upon electricity, whereas agglomeration and induration of pellets rely heavily on natural gas.

Indirect energy again accounts for most of the total energy required; more than 53% of the pellet total is indirect. This indirect energy includes: (1) embodied energy in materials consumed, (2) the energy required to produce, refine and transport fuels consumed, (3) generation losses in providing electrical power, and (4) miscellaneous other factors in pellet production and transport.

Recent trends in pellet production suggest two things. First, energy intensities probably have declined as operation experience with relatively new technology increases and economies of scale continue to be understood. Heat recuperation at kilns and other energy conservation efforts could reduce energy requirements further. Second, the energy intensity of pellets may go up as operators are forced to substitute other fuels for natural gas which is now used in most kilns and as non-magnetic ores are substituted for magnetic taconites. Added pollution abatement efforts could also raise total energy requirements. Although energy requirements for pellets probably declined over the past ten years, they will probably remain close to present levels into the near-term future.

Comparison of Natural Ore to Pellet Iron Preparation

Energy. Pelletized iron ore delivered to U.S. blast furnaces requires more than 2.5 times as much total energy as natural ore concentrates per net ton Fe. If only mine-site preparation is considered, and transportation to blast furnaces not included, the difference is even greater. Preparation of pelletized Fe requires more than six times as much energy as preparation of natural ore concentrate Fe. Pellet production depends primarily upon electricity and natural gas whereas natural ores are most dependent upon electricity and diesel oil. More than half of the energy consumed by both ore preparation processes occurs as indirect energy.

Labor. The preparation of pelletized iron ore requires more labor than natural ore concentrates, based on calculations made from raw data collected for the Minnesota Energy Agency.[13] The data base includes employment and production figures for six operating pellet plants and three natural ore concentrators in Minnesota for 1972 and 1973. Corrected for Fe content and averaged for both years and all companies, calculations indicate that pellet plant production was 4380 tons of pellets per year per employee whereas natural ore production was 5660 tons of comparable Fe content ore per year per employee. The natural ore worker's production of Fe, therefore, was 29% greater than that of the pellet plant worker's.

Capital. Estimates of expansion costs made by four pellet companies in 1973 averaged approximately $50/gross ton of annual pellet capacity added.[14] Comprehensive engineering documents entered as public record in the case of Reserve Mine Co. and the State of Minnesota[15] detail 1975 cost estimates for constructing a complete, new pellet plant near Babbitt, Minnesota. Calculations based on this record indicate a $75/gross ton of annual pellet capacity. These figures have been verified as reliable by pellet plant operators.

In contrast, new construction or added production capacity for natural ore concentrates is virtually nonexistent. Therefore, estimated capital costs are much less reliable for natural ore production. Operators estimated costs ranging from $4 to $25/gross ton annual capacity if they were to expand.[16] A reasonable average might be $10 to $15. This range puts pellet production at five times more capital intensive than natural ore production.

Embodied Costs of Pellets. The increased energy, labor and capital costs of pelletized iron ore, in comparison to natural ores, characterize the differences between iron ore burdens for the blast furnace. But this is not the point of indifference. Although they may contain the same quantity of Fe, pellets and natural ore concentrates react quite differently in the blast furnace and do not reach a point of indistinction until they emerge as the molten iron product of the blast furnace.

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by

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The added costs of pellets must be considered in evaluating the total effects of this ore preparation technology, but the changes that pellets cause in the blast furnace must also be evaluated. In addition, other concurrent changes in blast furnace practices must be considered. Using the energy calculations presented, the following section evaluates the total energy changes attributable to pellets in the blast furnace.

3. BLAST FURNACE ENERGY, LABOR AND CAPITAL CHANGES WITH PELLETS

Introduction

Blast furnaces chemically reduce the iron oxide of ore to molten iron. In the huge, modern blast furnace, iron ore is continuously charged at the top along with coke, limestone, dolomite and other materials. At the bottom, hot air (the blast or "wind") is blown in through small nozzles called tuyeres. The hot air comes in at 1400° to 2100° F. and ignites the coke, increasing bottom temperatures to some 3400° F. This temperature is sufficient to melt the charge, which is tapped off as molten iron and separated slag. Thus, as the charge sinks down through the furnace it heats and is reduced by the combustion of coke. Thus oxygen is removed from the iron oxide ore. The limestone and dolomite reacts with impurities in the iron ore (e.g., phosphorous, silica, manganese, aluminum, magnesium) and coke (e.g., sulfur, ash) to form the slag. Some carbon from the coke and silica from the ore (reduced to silicon) dissolve in the molten iron.*

When pelletized ore is substituted for natural iron ore feed in the blast furnace, three main changes in the firing occur. These are: (1) improved gas to solid contact, (2) increased quantity of gas in the blast furnace, and (3) reduced waste to be removed. Each of these

*These impurities in the iron are the main chemical objectives of the subsequent steelmaking furnaces. Ferroalloys are also blended with the molten iron in steel furnaces.

contributes to reduced energy requirements per ton of molten iron produced and is discussed separately below.

First, the hard, spherical structure of iron ore pellets increased the air permeability in blast furnaces. Previously, when larger proportions of natural ore fines were charged, channeling of the hot air occurred and coarse natural ore lumps took hours to heat. However, pelletized iron ore burdens improved the gas to solid contact ratio in blast furnaces and thus reduced burden heating times and increased chemical reaction efficiencies.

The second change resulting from the increased permeability of pellet burdens was the opportunity to blow more hot air into the furnace since the blast would move through the burden more easily. To retard gases with reducing potential from being blown out of blast furnaces, pressurized tops were developed. Wind under pressure resulted in more pounds of gas in the blast furnace and thus in another improvement in chemical reactive efficiency.

A third important energy change resulting from pelletized ore involves the iron content of ore burdens. Pellets average between 60% and 65% iron whereas domestic natural ore today averages between 50% and 55% iron. The ten percent difference means that the natural ores include larger fractions of impurities (especially phosphorous, silica, manganese and aluminum). Chemical reactions in the blast furnace are required to remove impurities from the iron and incorporate them in the slag waste. Coke provides the energy for the chemical reactions and limestone, dolomite and other minor fluxing agents provide the bonding chemicals. Because pellets have a higher percentage of iron per ton of charge, there is less chemical work needed to remove the impurities. Thus, less slag is produced and less coke and flux are required with pelletized iron ore burdens.

These three changes (improved gas to solid contact, increased gas in the blast furnace and reduced quantity of waste to be chemically removed) are a consequence of pelletized iron ore burdens and cause substantial savings of direct energy required for blast furnace reduction of iron.

There are several other changes in blast furnace operation that have occurred concurrently with the introduction of pelletized iron ore burdens. The temperature of the hot air blast has tended to be increased from about 1000° F. before pellets to an average of about 1800° F. with pellets. The hot air blast is heated by a series of heat recuperation stoves and the combustion of blast furnace gas. Another change is the injection of fuels (fuel oil, natural gas, coke oven gas, blast furnace gas, tar and pitch, and others) and oxygen through the tuyeres to speed the combustion process in the bottom of the blast furnace. A third change is the expanded use of self-fluxing or super-fluxing sinter. All three of these changes (increased blast temperatures, injection of supplemental fuels and expanded self-fluxing sinter), along with the increased embodied energy of iron ore pellets as a substitute for natural ores, are associated with increases in energy use per ton of molten iron produced.

With some energy factors increasing over time and others decreasing as pelletized ores assumed a larger proportion of the blast furnace iron burden, a <u>total energy trend</u> must be calculated to determine if pellets require more or less energy than natural ore concentrates. A total energy trend is calculated by determining total energy requirements per ton of molten iron for each year and plotting the annual total energy figures. Each year is characterized by actual rates of pellet charge, coking rates, injected fuel rates, flux rates and others recorded annually for blast furnace practices by the American Iron and Steel Association and other agencies. (See Table A-2.)

1975 Total Energy of Blast Furnace

The total energy required per ton of molten iron can be calculated by converting to Btu and summing the energy values of all fuels and materials put into the blast furnace, giving proper Btu credit for byproduct blast furnace gases extracted from the blast furnace, and dividing by tons of iron yield. Annual industry-wide averages for rates and quantities are published[17] and the energy conversion factors presented in the appendix (Table A-1) are used. Pellets and natural ore concentrates are each assigned the Btu values as calculated in the preceding sections for the standard cases and weighted according to the percent of iron charge observed for each year.

Pellets and natural ore are the two largest indirect energy components to vary with recent blast furnace practices. Neither these nor other indirect energy components (e., limestone, dolomite and other flux rates) have been incorporated in previously published assessments of blast furnace energy changes.[18]

Sintered iron ore is relatively constant and a long established charge factor in blast furnace burdens. Its percentage of iron burden varies only slightly over the 1955-75 period considered. Therefore, a value calculated by Battelle-Columbus Laboratories[19] for sintered iron ore of 2.47 million Btu/net ton sinter (or at 41% iron content, 6.0 million Btu/net ton Fe) is used.

Table A-2 presents the blast furnace total energy calculation for 1975. In that year, 23.45 million Btu were required to produce a ton of molten iron. Omitted from this total energy figure are minor energy values that would be required to provide the capital structures of the blast furnace, coke ovens, pellet plants, etc.; minor energy values for preparation of the small quantities of mill scale and scrap that are charged into the blast furnaces; and other minor indirect energy requirements.

Also in Table A-2 is a summary of the total energy calculations for blast furnace operations for 1955 and 1965 as well as 1975. Over this time period, the energy required to provide the iron ore burden increased as the percentage of pellets increased. Also, beginning in the early 1960s, the practice of injecting supplementary fuels caused increases in energy requirements in the blast furnace. On the other hand, the reduced coke rate and, to a much lesser extent, the reduced flux rates produced a significant decrease in energy requirements per ton of molten iron.* The total energy requirements per ton of molten iron for each year of the 1955-1975 period are plotted as Figure 3. The resulting trend shows a significant energy decrease per ton of molten iron from 1955 to 1963. During this period, the energy savings resulted from the decreased coke rate more than compensating for increased embodied energy of pelletized ore. From 1963 through 1975, the total energy per ton molten iron has remained nearly constant. During this period, the coke rate continued to decline, but supplemental fuel injection nullified further energy savings.

The observed increased use of pellets and sinter for the full period 1955 to 1975 is associated with a 27% reduction in energy requirements in the blast furnace. Partly offsetting this blast furnace energy savings are the increased embodied energy requirements of blast furnace inputs, especially the iron ore burden.

*Certain other factors are assumed to have remained constant over the time period analyzed.

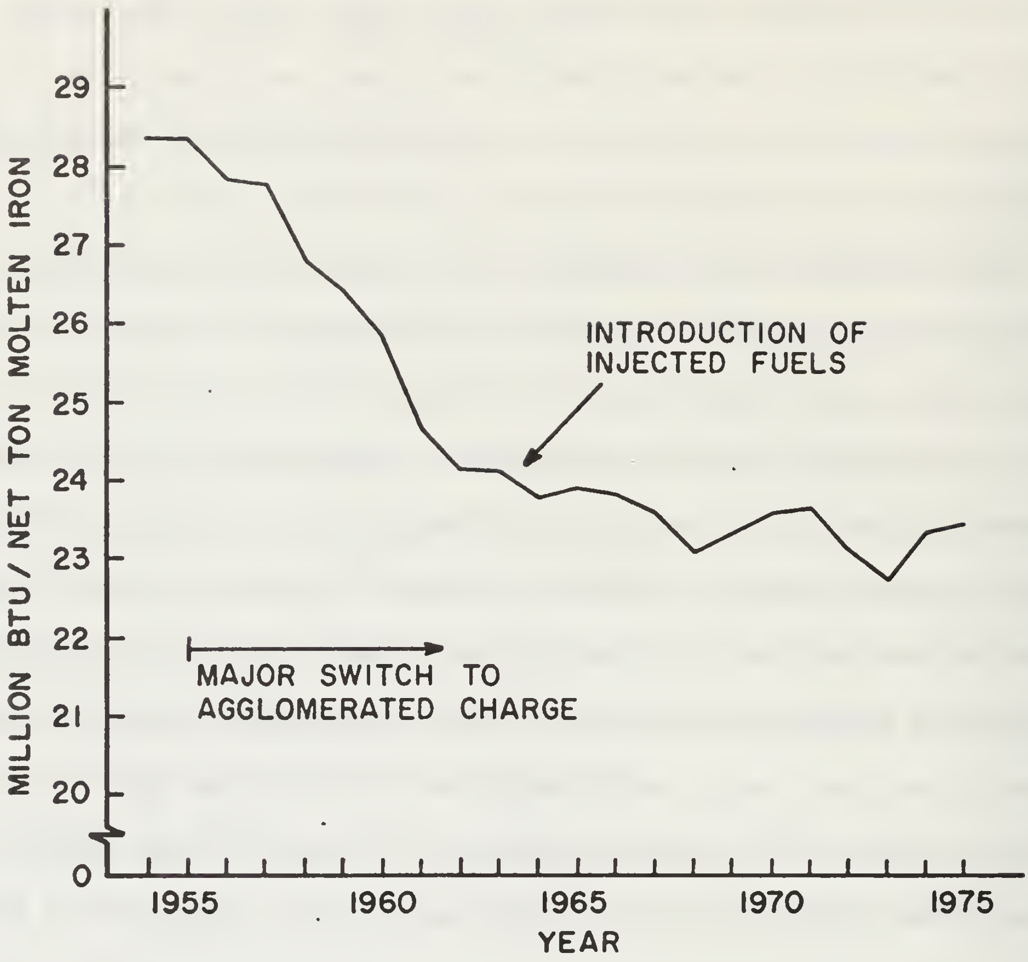

Figure 3. Total Energy Trend for U.S. Blast Furnace Production of Molten Iron.

The net result, however, is a 17% conservation of total energy required per ton of molten iron produced. This energy conservation can be attributed to pellets and sinter because agglomerate burdens significantly improve the physical and chemical characteristics of blast furnace smelting.

<u>Do Natural Ore Pellets Save Energy?</u>

Could even larger energy savings be accomplished by pelletization of natural ores with their higher initial Fe content? Natural ores currently mined tend to have twice the Fe content or better than taconite ore (50+% vs. 25% Fe). If just the iron content is considered, one might suggest that natural ore pellets would provide the same energy conservation in the blast furnace as taconite pellets, but provide additional energy savings at the mine-site with pelletization of richer crude ores. There are two main reasons why the application of pellet technology to natural hemitite ores does not conserve energy.

The first reason involves the chemical structures of the two ores. Magnetic taconite ($Fe_2O_3 \cdot FeO$) is converted to hemitite (Fe_3O_4) during pellet induration. This chemical reaction produces an exothermic heat release which is calculated to be 605,672 Btu/net ton Fe.[20] This exothermic heat release is 55% of the natural gas requirement and 37% of the total energy requirement for "agglomeration and induration" calculated for the standard pellet production case (Table 2). Since natural ores are already hemitite, there is no exothermic heat release when they are indurated. What does occur with induration of some natural ore pellets, however, is that water of crystallization is vaporized. This loss on ignition (LOI) can amount to 9% of the weight of natural ore pellets [21] and requires added energy in the kiln or grate to indurate these natural ore pellets. For example, I calculate for a geothite ore using an industrial estimate [22] of 2000 Btu/lb. of crystaline water, 643,000 Btu/net ton Fe required to drive off the contained water of crystallization. The LOI for taconite is near zero. Therefore, because of ore chemistry, natural ore (hemitite and goethite) pellets do not benefit from an exothermic heat release and on the other hand are handicapped with an extra heat requirement for LOI.

The second and most important reason natural ore pellets do not conserve energy involves the difference in physical structure of the ores. Natural iron ore has an unconsolidated, earthy structure which includes many very small particles and a large clay fraction. The extensive leaching of silicates and carbonates that geologically produced the high concentrations of Fe (some over 65% Fe natural), left the ore soft and composed of a wide range of particle sizes. Taconite on the other hand occurs as a very hard, metamorphosed rock that must be intensively crushed and ground to produce a particle size that will allow concentration of the Fe content. Such grinding (usually 80% minus 325 mesh) produces a much more uniform particle size and one with an average particle size some 10 times larger than the largest clay particles of natural ore.

The smaller and more variable particle size of natural iron ore cause three problems when pelletized.

(1) Permeability is reduced. The fine particles in a heterogenous particle array impede vacuum disc filtering and thereby increase the moisture content of filter cake. High moisture produces large green balls with enough plasticity to deform before induration. Also, when the degree of heterogeneity varies sporadically, moisture control becomes

erratic. Within local sections of the same pit, the degree of heterogeneity of natural ore particle sizes can vary greatly because of variance in the original leaching that concentrated the ore. Variable moisture, along with variable particle size, produces variable ball sizes: large balls will deform plastically, small balls will pack potential pore spaces. In both cases (plastic deformation and denser packing), permeability through the green ball bed is reduced. Lower permeability causes an increase in energy requirements to indurate the pellets. Non-spherical and variable sized pellets will in turn reduce the permeability in blast furnaces and again increase energy requirements.

(2) A second problem is that natural ore pellets are weaker. To accommodate the LOI, the natural ore pellet itself must be porous and permeable. Bentonite is used in this case to create the pores, but the resulting porous pellet is weakened. Also, a pellet bed that is not indurated thoroughly (because of packed or deformed balls) will result in weak pellets. And finally, great variance in particle size causes differential expansion when indurated and thus can result in cracked or weakened pellets. Such weak pellets break more easily when handled and produce dust or small pellet fragments. These fine materials further reduce permeability of blast furnace burdens. One experienced blast furnace operator indicated that 10% fines are enough to stall the blast furnace and that's why a high "Q" factor (usually greater than 94) is demanded for pellets.[23] Experience with natural ore pellets indicates difficulty in maintaining even an 88 Q.[24]

(3) The third problem is that concentrating Fe is more difficult with small and variable sized particles. The fine particles of natural iron ore are colloidal whereas the minus 325 mesh screen size of a

taconite grind is about 40 times larger than the colloidal-noncolloidal boundary. Therefore, specific gravity methods of concentrating natural ores are restricted and natural ore is not magnetic, of course, so magnetic concentration methods are impossible. As a result, iron content of most natural ore pellets would be dependent upon the grade of ore mined; pelletization would simply remove moisture.

In conclusion, pelletization of natural ore requires more energy at both the mine and the blast furnace as well as producing an inferior pellet in other ways when compared to taconite pellets. The shift to pelletization technology, therefore, involves an interesting sequence of events. The post-World War II scare of running out of high grade natural iron ore invoked two responses: (1) search for more natural iron ore deposits, and (2) develop the pelletization technology to convert low grade taconite ores into acceptable blast furnace feed. The success of both responses firmly quelled the iron ore depletion scare by the late 1950s. But it was the taconite pellet technology that held revelations for the future. The increased physical productivity in the blast furnace (more tons molten iron/blast furnace-day from a given furnace) with pellet charges meant that new blast furnaces did not have to be built to meet the increased production demanded by BOFs. As a positive side effect, the pellets were also found to reduce coke requirements in blast furnaces. It was subsequently learned that pellet technology could not be applied effectively to the expanded discoveries of natural ore. Natural ore fines and coarse material became a second rate product. Thus, pellet technology turned a waste rock into a favored resource and made discoveries of high grade natural ores, the basis of the iron ore exhaustion fears originally, obsolete.

Blast Furnace Productivity

The improved permeability of pellet burdens, the subsequent top pressurization, the injection of supplemental fuels and the increased temperature of air blown into blast furnaces have all contributed to faster chemical reduction of the blast furnace charge. Faster reduction means faster molten iron produced from one blast furnace. Thus, blast furnace productivity doubled from 1955 to 1975, as shown in Figure 4.

There are two distinct phases to the faster molten iron production from blast furnaces. From 1955 to about 1963 is one phase and correlates with the rapid increase in agglomerated iron ore charges.* The second phase runs from 1963 through 1975 and continues to the present. This second phase is distinguished by the blast furnace practice of injecting supplemental fuels.

Production increased by over 500,000 tons per blast furnace-day in the first phase and total energy requirements for molten iron production fell by more than 4 million Btu per ton. It was the physical and chemical changes that the newly introduced agglomerates brought to blast furnace burdens that caused these production increases and energy savings. The improved gas to solid contact, the increased quantity of gas in blast furnace, and the reduced waste to chemically remove as slag resulting from pellets and well formed sinter charges increased both the chemical efficiency and rapidity of blast furnace reactions.

The second phase of molten iron productivity was allowed by the changes pellets made in blast furnace burdens. The increased permeability first allowed higher blast temperatures which, in turn, allowed the injection of supplemental fuels into the blast furnace. The added fuels further speeded the chemical reduction process, but with added energy expenditures. Thus, productivity in the second phase was

*For example, agglomerates increased from less than 20% of charge in 1955 to about 62% of charge by 1963. In subsequent years, agglomerates continued to increase but at a slower rate until they comprised just over 80% of blast furnace burdens by 1975.

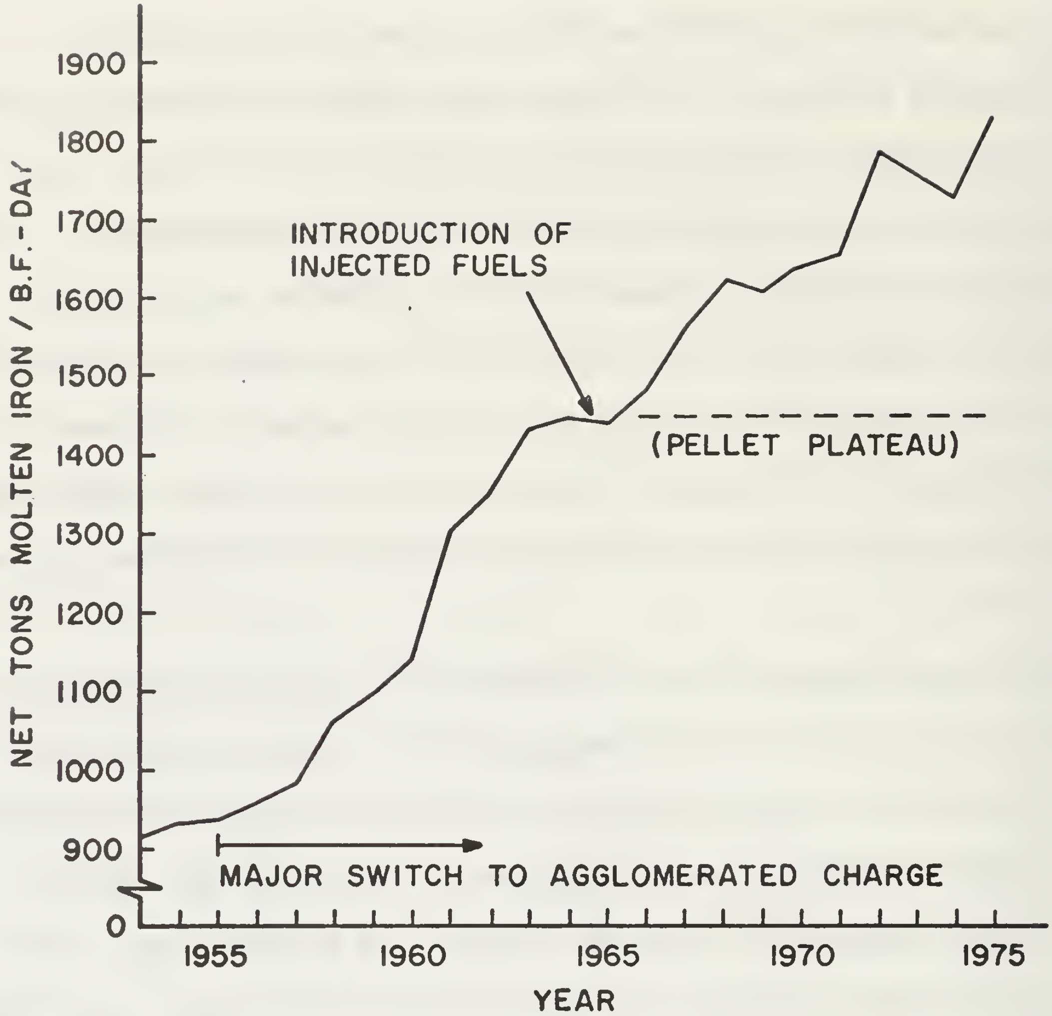

Figure 4. Average U.S. Production of Molten Iron Per Blast Furnace-Day

DATA SOURCE: AISI

stimulated by consumption of supplemental energy. The point of deflection in energy savings in the early 1960s is apparent on Figure 3. Increased productivity from agglomerate charges appears to have reached a plateau in the early 1960s as indicated on Figure 4.

Faster production of molten iron changed both labor and capital requirements, as well as energy, per ton of product. Thus, the requirements for molten iron changed substantially and for several reasons since the first introduction of pelletized ore burdens in 1955. The following sections discuss net changes in the factors of molten iron production attributable to pelletized ores. The net changes are calculated for total energy, direct labor, and direct capital. These changes are calculated as net changes for the entire molten iron system starting with the mining of iron ore and follow through the blast furnace production of molten iron.

Changes in Total Energy with Pellets

Two situations are considered in calculating net total energy requirements for molten iron production. One is based on the observed shift in forms of iron fed to blast furnaces between 1955 and 1975; natural ore feed declined by 63% and agglomerates (pellets plus sinter) increased by this much. The second situation is hypothetical and compares energy requirements for a 100% shift from all natural ore to all agglomerate burdens. In both situations, net energy requirements are calculated and attributed to pelletized ores.

For the first energy situation considered, observed rates of blast furnace iron ore feed shifted from 81.5% natural ore in 1955 to 81.6% pellets and sinter in 1975. This observed shift in ore preparation caused a 170% increase in total energy required per ton of Fe* at the

*Iron ore feed rates to blast furnaces average 0.975 ton Fe-in-ore/ton molten iron. Minor losses of iron ore occur in transport and in periphery blast furnace handling. Therefore, a 1.00 ratio of Fe-in-ore produced at the mine to Fe-in-molten-iron is used.

mine. (See Table 3.) Energy requirements for transport of ore to blast furnaces declined slightly with the rise in pellets as there is less waste rock (gangue) to be transported. An adjustment in the net total energy calculation is made for sinter as the Battelle process analysis [25] found sintered ore to require slightly more energy than I calculate for pellets. The observed shift in ore preparation from 1955 to 1975 therefore resulted in an 81% increase in total energy to deliver iron ore to U.S. blast furnaces. The energy required for ore preparation, however, represents only a minor component in the total energy need to produce molten iron.*

Declines in coke consumption, the major energy component, more than offset energy increases for ore preparation. Total energy for coke consumption declined by 30% from 1955 to 1975. Reduced energy requirements for fluxes and increased blast furnace gas recovery added to the energy savings. On the other hand, injection of supplemental fuels contributed to greater energy requirements per ton molten iron produced. The net result for the entire molten iron production system in total energy required per ton molten iron produced, given the 1955 to 1975 observed shift in practices, is a <u>reduction of 17%.</u>

In the second energy situation, a hypothetical comparison is drawn between 100% natural ore burdens with 0% agglomerates and 0% natural ore with 100% agglomerates (comprised of 75% pellets and 25% sinter). Also the effects of injecting supplemental fuels into the blast furnace, a practice which began essentially in 1963, is deleted. This is accomplished by using the period 1955 through 1962 for calculating a rate at which coke

*In 1955, iron ore preparation and transport contributed only 11% of the total energy required to produce molten iron. Ore preparation has become more energy intensive and its relative contribution to molten iron production was 20% in 1975.

TABLE 3

OBSERVED CHANGE IN TOTAL ENERGY REQUIRED PER TON MOLTEN IRON
WITH MAJOR PELLET INTRODUCTION FROM 1955 to 1975*

Process	Btu/Net Ton Molten Iron 1955	1975	Difference	% Change 1955-1975	% of Total Energy Change 1955-1975
I.O. Preparation at Mine	1,283,370	3,462,608	+2,179,238	+170%	+7.7%
I.O. Transport	1,253,074	1,127,126	- 125,948	-10	-0.4
Addition for Sinter Used	113,556	210,266	+ 96,700	+85	+0.3
Subtotal: IO Delivered to BF	(2,650,000)	(4,800,000)	(+2,150,000)	+81	(7.6)
Coke Consumed	27,500,000	19,250,000	-8,250,000	-30	-29.1
Fluxes	90,000	60,000	- 30,000	-33	- 0.1
Injected Fuels + O_2	2,030,000	3,660,000	+1,630,000	+80	+ 5.8
Other Materials + Elec.**	1,590,000	1,590,000	-0-	-0-	-0-
By-Prod. BF Gas (credit)	-5,530,000	-5,910,000	(-)380,000	- 7	-1.3
TOTAL (net)	28,330,000	23,450,000	-4,880,000	(-17%)	-17%

Abbreviations: I.O. = Iron Ore; BF - Blast Furnace.

*Based on observed BF feed rates for natural iron ores (1955=81.5%; 1975=18.4%) and agglomerates (pellet plus sinter: 1955=18.5%; 1975=81.6%), post 1963 supplemental fuels injection, and other actual changes in BF operation.
**Held constants as in Table A-2.

consumption declined per percent of agglomerates introduced and then projecting this rate (averaging -138,800 Btu total coke energy/ntmi/1% agglomerate increase) from the 18.5% agglomerates of 1955 to 0% agglomerates and projecting ahead from the 1962 level of 40% agglomerates to derive a 100% agglomerate charge. (See Table 4.) Other blast furnace practices were adjusted in an effort to remove the effects of supplemental fuel injection. The energy requirements for iron ore preparation and transport calculated for natural ore (Table 1) and pellets (Table 2) were used for the two cases as well as making some allowance for sinter in the 100% agglomerate charge case.

Total energy is reduced by 36% per ton of molten iron with the hypothetical shift from an all natural ore to an all agglomerate charge.* In absolute terms, this is more than 10 million Btu/ntmi. If one were to take the projected all agglomerate charge (without supplemental fuel injection) as setting the minimum level of energy consumption attributable to pelletized ores, it would be possible to identify energy savings beyond current practices. An all agglomerate charge would consume 4 M Btu/ntmi less than occurred in 1975. Thus, the full impact of pelletization could provide, beyond 1975 levels, an additional <u>18% potential energy saving.</u>

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*Double checking this calculation, I find that the 1955 to 1962 average rate of change of total energy is 109,200 Btu/ntmi/1% increase in agglomerate charge and yields similar results to Table 4; i.e., 30.35 M Btu/ntmi for an all natural ore charge and 19.75 M Btu/ntmi for an all agglomerate charge.

TABLE 4

CALCULATED ENERGY REQUIREMENTS FOR MOLTEN IRON WITH 0% and 100% PELLET (AND OTHER AGGLOMERATE) BURDENS

Process ∔	Btu/net ton molten iron			% Change 0-100% Agg.	% Change from 0% Agg. Total energy/n tmi
	0% Agg. burden*	100% Agg. burden**	Difference		
I.O. Preparation at mine	644,450	4,062,975	+3,418,525	+530%	+11.3%
I.O. Transport to B.F.	1,290,000	1,090,400	-199,600	-15	-0.7
Addition for Sinter	-0-	212,834	+212,834	-	+0.7
Sub-Total: I.O. delivered to B.F.	(1,934,450)	(5,366,209)	(+3,431,759)	+177	(+11.4)
Coke Consumed	30,070,000	16,200,000	-13,870,000	-46	-45.9
Fluxes	100,000	60,000	-40,000	-40	-0.1
Injected B.F. Gas	2,030,000	2,030,000	-0-	-0-	-0-
Other Materials & Elec.	1,590,000	1,590,000	-0-	-0-	-0-
by-prod. B.F. gas (credit)	-5,530,000	-5,910,000	-380,000	-7	-1.3
TOTAL (net)	30,194,450	19,336,209	-10,858,241	(-36%)	-36%

Abbreviations: I.O. = Iron Ore; B.F. = Blast Furnace;
Agg. = Agglomerates, includes pellets, sinter and other agglomerated iron charge.
ntmi = net ton molten iron.

∔ Energy requirements for "I.O. Preparation" and "I.O. Transport" according to total energy analysis presented in Tables 1 and 2; for "sinter" adjusted according to Battelle [19] process analysis; for "coke consumption" projected from coke rate of change per percent of agglomerates charged calculated from my total energy trend between 1955 and 1962 (years prior to supplemental fuels injection); for "fluxes" observed rates for 1950 assumed for 0% agg. and 1975 assumed for 100% agg.; for "injected B.F. gas" held constant at 1966-75 average rate; for "other materials" held constant as in Table A-2; for "by-prod. B.F. gas" 1975 observation used and average of 1966 to 1975 projected for 0% agglomerate burden.

* 0% Agglomerate, 100% Natural Ore Burden

** 75% Pellet, 25% Sinter, 0% Natural Ore Burden

Changes in Direct Labor at the Mine and Blast Furnace with Pellets

To calculate net labor (and net capital) changes associated with the introduction of iron ore pellet technology, other data bases were used. A cost schedule for molten iron production was constructed to identify the relative importance, measured in dollars costs, of the major process sectors contributing to molten iron production. (See Table A-3.) The relative component cost (by process sector) can be subdivided into relative costs attributable to: 1) labor -- "employee compensation", 2) capital -- "property type income" plus "indirect business taxes", and 3) inputs--purchased energy, materials and services. This disaggregation is accomplished by using Bureau of Economic Analysis (BEA) derived ratios to total output for labor, capital, and inputs for the two digit industrial classification.[26] Relative scaling of labor and capital costs separately, as opposed to just scaling total costs, provides a more refined ratio of each sectors' labor and capital component. (See Table A-4.) The magnitudes of the labor and capital changes over the 20 year time period were determined from U.S. Census of Manufacturing and Bureau of Labor Statistics data.

Three situations are considered in analyzing labor changes caused by the shift to pelletized iron ore. (See Table 5.) First, the observed shift in iron ore preparation that occurred during 1955 to 1975 is used. In this situation, the ore form shifted from predominantly natural ore (81.5% in 1955) to predominantly agglomerated ore (81.6% in 1975). As discussed previously, agglomerated ore is more labor intensive per ton of iron shipped than natural ore and mine-site labor was found to have increased by 17%. Weighting the mine-site labor increase by its proportion of total molten iron labor (16.2% weighting factor), yields a +2.8% contribution to total molten iron labor from changes in observed ore

TABLE 5

DIRECT LABOR CHANGES CAUSED BY PELLETIZED IRON ORE AT MINE AND BLAST FURNACE PER TON MOLTEN IRON

Row	Situation #1: Observed Change, 1955-75	Situation #2: All Agglom.; Restricted BF Prod.	Situation #3: Pellets Allow BF Prod.
1) IO mining* (man-hr/ntmi)	+17%	+29%	+17%
2) Ratio of IO mining to MI**	(x) .162	(x) .162	(x) .162
3) IO contribution to MI	+ 2.8%	+ 4.7%	+ 2.8%
4) BF operations+ (man-hr/ntmi)	-33%	-21%	-27%
5) Ratio of BF operations to MI**	(x) .406	(x) .406	(x) .406
6) BF contribution to MI	-13.4%	- 8.5%	-11.0%
7) Net labor change (man-hr/ntmi) (sum of Row 3 plus Row 6)	-10.6%	- 3.8%	- 8.2%

Abbreviations: IO - Iron Ore; MI - Molten Iron; BF - Blast Furance; ntmi - net ton molten iron: Agglom. = Agglomerates and includes pellets, sinter and other agglomerated iron charge.

Situations:

#1: Observed changes involve shift from 81.5% natural ore feed in 1955 to 18.6% natural ore in 1975 and increased BF output per man-hr as reported by the 1954 and 1972 Census of Manufacturing and to 1974 by the Bureau of Labor Statistics.

#2: Considers mining labor intensity increase for a hypothetical shift from no agglomerates to all agglomerate ore production and crediting pellets with BF labor productivity increases only up to the 1963 "pellet plateau" using 1954 and 1963 Census of Manufacturing data.

#3: Observed change in ore form from 1955 to 1975; 1/2 of BF productivity post-1963 credited to pellet charge for allowing fuel injection and higher blast temperatures.

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*Calculated from Minnesota Energy Agency raw data[13]; 1972 and 1973 average differences between natural ore mining and pellets apportioned according to percent of each mining activity assumed to supply ore.

**MI = complete molten iron production system as detailed in total cost schedule of Table A-3.

+Calculated from Census of Manufacturing and Bureau of Labor Statistics data and adjusted for time periods considered as indicated in situation explanations.

preparation from 1955 to 1975. Labor savings at the blast furnace more than offset mine-site increases, however. And BF labor reductions are primarily caused by the pelletized ore burdens that were being introduced. Pellets increase the rate of blast furnace production significantly (doubling output in some cases) by increasing the chemical efficiency of reduction in the more permeable burden. Since 1963, injection of supplemental fuels, automation, and the reduced handling of other input materials have also contributed labor savings in the blast furnace sector. The result is that the increased labor required to provide the improved iron ore burden was over-compensated for by labor reductions in blast furnace operations per ton molten iron produced.* Blast furnace area man-hours/ntmi declined by 33%** between 1955 and 1975. Therefore, using the percent of total molten iron labor that is attributable to blast furnace labor (40.6% from Table A-3) times the 33% decline in BF labor gives a sector decline of -13.4%. Net labor changes from 1955 to 1975 per ton molten iron therefore amounted to a 10.6% reduction. Much of this labor savings can be directly

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* Other reductions or increases that occurred in coal mining, flux mining and transportation have not been considered in the labor (or capital) change analysis. Therefore, only direct labor (and direct capital) changes in ore preparation and blast furnace operations are considered.

** Census of Manufacturing shows a 54% increase in net tons pig iron/blast-furnace-and-steelmill employee from the 1954 to the 1972 census. Bureau of Labor Statistics show 51% increase in output/production worker, 40% increase in output/all employees, in steelmills from 1955 to 1974. Therefore, 50% increase in output per employee as approximate average is used and converts to a 33% reduction of man-hours per net ton molten iron.

attributed to pelletized iron ore burdens although not all of it.* Therefore, two other labor change situations were calculated based on other assumptions.

Labor situation number two assumes mining labor intensities increased as they would if there was a complete shift from no agglomerate ore preparation to 100% agglomerate preparation. Also assumed in Labor #2 is no credit for increased BF productivity beyond the "pellet plateau" of 1963. Labor requirements for molten iron are still reduced under these more restrictive assumptions, but by only 3.8%. The third labor situation is a compromise of the first two and probably is most realistic. Labor #3 assumes mining labor intensities to increase according to the observed historic shift in ore preparation forms. In addition, BF labor productivity increases from 1955 to 1963 are credited to pelletized ore burdens plus one-half of the following productivity gains following the 1963 pellet plateau. The reasoning here is that increased permeability of pellet burdens allowed more heat to be flown into the blast furnace in the form of supplemental fuel injection, oxygen injection, and greater pre-heated blast air. The higher resulting temperatures were the direct cause of faster molten iron production after 1963, but pellets indirectly paved the way for greater productivity by providing improved permeability. The resulting change in direct labor at the mine and the blast furnace under these assumptions is an <u>8.2% decrease</u> in man-hours per ton molten iron.

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* In addition to changes in technology (of which pelletized ore burdens and supplemental fuel injection are specifically considered here), other influences affect change in labor productivity, but are not considered specifically here. These other influences include capital investment per worker, business trend, skill of the work force, managerial skill, labor-management relations, and efficiency of materials handling.

Changes in Direct Capital at the Mine and Blast Furnace with Pellets

A similar three situation analysis has been calculated for net capital changes attributable to pelletized iron ore burdens. (See Table 6.) Pellet plants require much more capital investment than natural ore mines. In the first capital change situation, the observed shift in ore form from 1955 to 1975 yields a direct capital increase for mining of 127% and ore preparations represents 32.1% of total capital required to produce molten iron. Therefore, the shift in ore preparation contributed a 41% increase to total molten iron production. The faster production of molten iron from a given blast furnace meant less capital invested per ton molten iron produced.* Over the 1955 to 1975 time period, capital investment in dollars per net ton molten iron for blast furnace operations (including coke ovens, ore yards, and materials feeding) is calculated to have decreased by 45%.** The increased productivity from a given furnace when pellets are fired

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* Likewise, reduced coking coal consumption and reduced transportation of materials would decrease other capital investments, but changes in these sectors are not considered in this analysis. Therefore, only direct capital changes of iron ore mining and blast furnace operations are considered.

** Blast furnace productivity increased from 940ton/BF-day in 1955 to 1840ton/BF-day in 1975 for approximately a 100% increase. This increase in physical productivity was accomplished by two main developments: 1) increased pressures in BF which the permeability of pellets allowed, and 2) increased temperatures which was subsequently accomplished by injecting fuels. These two developments provided enough gain in BF productivity so that new BF construction was simply postponed throughout most of 1955 to 1975. (For the BFs that were constructed, a third gain in productivity--capital productivity--was accomplished by larger furnaces and the economics of scale they provided.) Only minor equipment modifications were required at various phases of the BF area (increased wind rates, more casting floor capacity, increased ore yard capacity, etc.) to gain up to 80% more productivity from a given BF. Increases beyond this level stressed multiple equipment limits and capital costs began to soar. Therefore, a 45% reduction in BF capital costs/net ton molten iron from 1955 to 1975 is assumed. This reduced capital cost is manifest in real dollars by the postponement of interest payments on the money that would have to be borrowed by steel-mills to construct new blast furnaces.

TABLE 6

DIRECT CAPITAL CHANGES CAUSED BY PELLETIZED IRON ORE

AT MINE AND BLAST FURNACE PER TON MOLTEN IRON

Row	Situation #1: Observed Change 1955-75	Situation #2: All Agglom.; Restricted BF Prod.	Situation #3: Pellets Allow BF Prod.
1) IO mining* (inv. $/ntmi)	+127%	+320%	+127%
2) Ratio of IO mining to MI**	(x) .321	(x) .321	(x) .321
3) IO contribution to MI	+ 41%	+103%	+ 41%
4) BF operations+ (inv. $/ntmi)	- 45%	-24%	-34%
5) Ratio of BF operations to MI**	(x) .308	(x) .308	(x) .308
6) BF contribution to MI	- 14%	- 7%	- 10%
7) Net Capital change (inv. $/ntmi) (sum of Row 3 plus Row 6)	+ 27%	+96%	+31%

Abbreviations: IO = Iron Ore; MI = Molten Iron; BF = Blast Furnace; ntmi = net ton molten iron; Agglom. = Agglomerates and includes pellets, sinter and other agglomerated iron charge.

Situations:

#1: Observed changes involve shift from 81.5% natural ore feed in 1955 to 18.6% natural ore in 1975 and increased BF productivity reduced BF investment dollars by an estimated 45% (see footnote in text).

#2. Considers mining capital cost increases for shift from no agglomerates to all agglomerate ore production and crediting pellets with only BF capital cost reductions from 1955 up to the "pellet plateau" of 1963.

#3. Observed changes in ore form preparation from 1955 to 1975; 1/2 of BF capital reduction post-1963 credited to pellet charge for allowing fuel injection and higher blast temperatures.

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* Calculated from industrial estimates and published records cited in text.

** MI = complete molten iron production system as detailed in total cost schedule of Table A-3.

\+ Calculated from AISI Annual Statistical Report record of BF productivity increases (in tons of molten iron/BF-day) and industrial evaluation of limiting factor costs for blast furnace investment as discussed in footnote in text.

contributed much of these savings. Blast furnace capital expenses comprised 30.8% of total molten iron capital investment; therefore, blast furnace savings contributed a 14% savings in total capital expenditures required to make molten iron. The net effect of the 1955 to 1975 shift to pelletized iron ores was to increase capital investment by 27% per ton molten iron produced. Therefore, increased demand for capital investment at the iron ore mine, given capital situation #1, was too great to be offset by savings at the steelmill and net capital investments increased. The conclusion that capital investments increased with pellets was found for all three assumed situations.

In capital #2 an extreme shift from no agglomerate ores to an all agglomerate ore preparation is assumed. Pellet credit to increased BF productivity, and thus reduced capital requirements, is halted at the 1963 pellet production plateau. The calculated capital investment for ore preparation and BF operation under capital #2 assumptions is a 96% increase.

The capital #3 situation assumes the observed shift in percent of natural versus agglomerate iron ore preparation for 1955 to 1975. Pellets are credited with the 1955 to 1963 BF productivity gains plus one-half of the subsequent gains on the reasoning that the permeable pellet burdens allowed the higher blast temperatures to be achieved. Under these most plausible assumptions, capital investment dollars per ton molten iron increased by 31% with pellets.

Comparison of Energy, Labor, and Capital Changes with Pellets

It is impossible at this time to weigh the three factors of molten iron production (total energy, direct labor and direct capital) so they could be added together to obtain a single cost evaluation of the shift to pelletized iron ores. These factors are still in states of "apples and oranges," therefore, they must be considered independently:

(1) Total energy savings are in Btu/ntmi with 17% savings attributed to the observed shift since 1955 toward the increased pellets burdens of 1975; 18% addition energy savings might be possible with 100% agglomerate burdens and no supplemental fuel injections, but BF production would be slowed.

(2) Direct labor in BF operations decreased substantially with pelletized ore burdens and more than offset increased labor intensities at iron ore pelletizing plants; net results yield a reduction of some 8% of man-hours per ton of molten iron.

(3) Direct capital expenditures have increased with pellets. Net change is probably 30% greater capital investment per ton molten iron required for the observed shift toward pellets.

(4) Despite the lack of a specific weighting factor to equate units, ensure comprehensive coverage, and avoid double counting, a general comparison of the factors of molten iron production can be made. Labor is by far the largest cost component [27] and labor requirements have declined with pellets. Total energy costs declined significantly with pellets also. Capital costs are generally a minor factor of total costs. The average percent of total labor in the final demand sector for "Fixed Capital Formation" for 1967 was only 12.3%[28]. Blast furnaces and iron ore pellet plants are more capital intensive than the average, but 15% of total costs may be generous enough. Therefore, in all likelihood, total costs of molten iron production have probably declined as a result of the introduction of pelletized iron ore technology.

Substitution of Production Factors

Substitution of one factor of production for another has occurred within the molten iron production system over recent decades. This substitution has taken different forms at iron ore mines than at steelmills. The decision to substitute one production factor for another is influenced primarily by relative changes in marginal productivities. Changes in unit costs can be used to calculate marginal productivity trends.

Figure 5 presents changes in unit cost ratios for energy, labor and capital for the iron and steel industry from 1940 to 1977.* Factor prices for energy are derived from the cost of coal per ton of coke, for labor from wages, and for capital from the interest rates on steel company bonds. (See Table A-5.) Changes in these factor prices illustrate changes in the entire molten iron production system; iron ore mining through blast furnace production. There are three phases in which these factor prices (marginal-products) change relatively.

Phase 1 runs from before 1940 to 1950. During this time, marginal-product costs for labor and energy were increasing more rapidly than capital costs. Therefore, capital investments were an attractive substitute for either labor or energy and it was the post-WW II period that witnessed extensive rebuilding and expansion of capital stock in the war worn steel industry.

Phase II extends from 1950 to 1970. It is characterized by labor and capital costs increasing consistently and exceeding modest energy price rises. Given these marginal-product costs, the tendency would be to substitute energy for labor first and energy for capital second. For the steel industry, the 1950s was also the period of responding to the iron ore depletion scare. Efforts were directed toward finding more iron ore deposits and toward developing pelletization technology. After the first shipments of pellets from

*These are similar to Hannon's [29] ratios for the total economy.

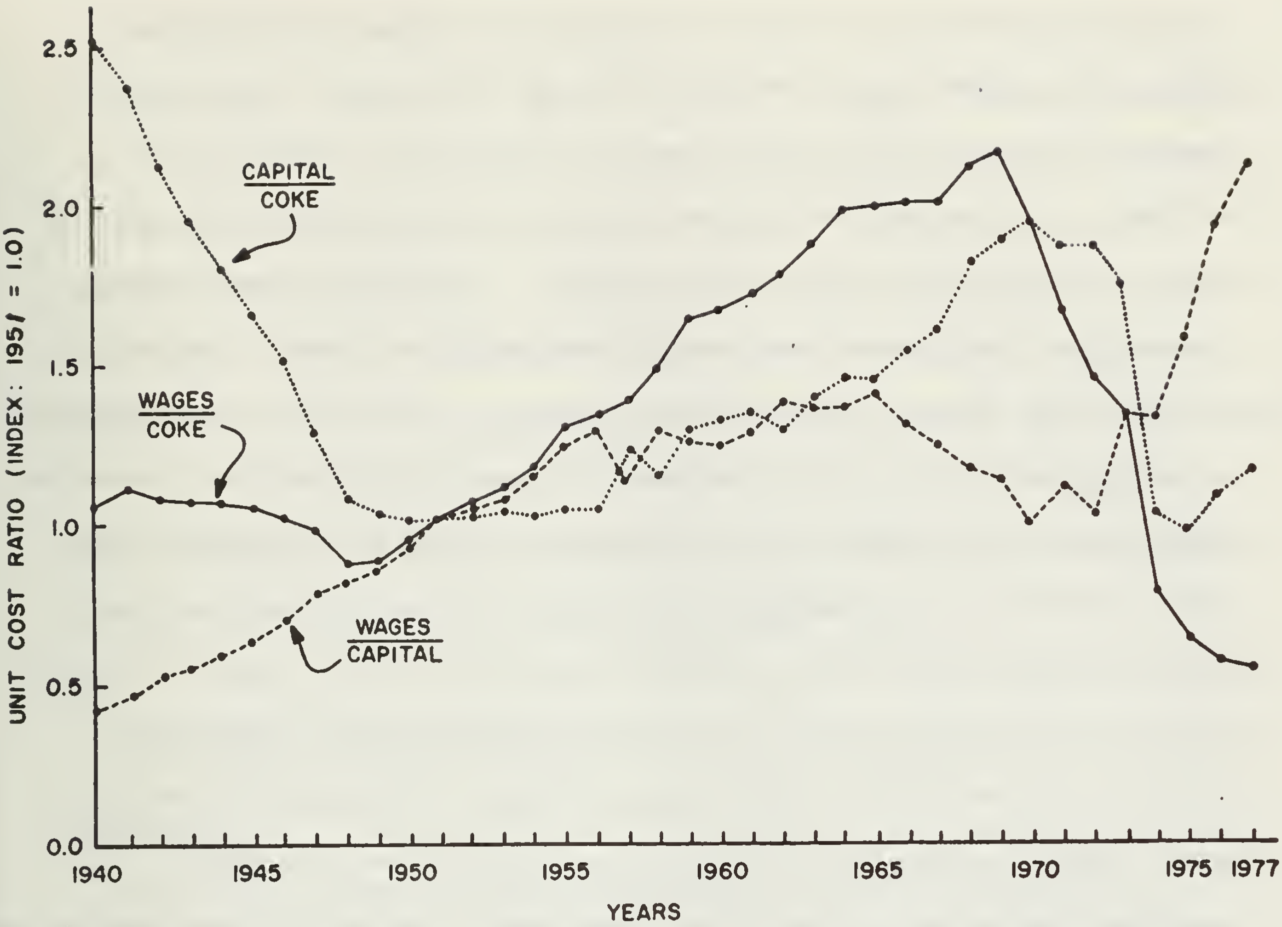

Figure 5. UNIT COST RATIOS FOR THE IRON AND STEEL INDUSTRY FOR ENERGY, LABOR, AND CAPITAL: 1940 - 1977.

Explanation:

CAPITAL = Market value of select AA bonds for major steel companies. Since new capital for captive pellet plants and other mines is often raised by major steel company bonds, this measure applies to the entire molten iron production system.

WAGES = Average total payroll costs for iron and steel industry wage employees from AISI. Although there are discrepancies, iron ore mines belong to the same union as iron and steel workers and the pattern of wage change in both has been very similar.

COKE = Cost of coal per ton of coke from U.S. Bureau of Mines data. Since coke is the major fuel of the molten iron production system, its cost is a reliable indicator of energy costs for the entire system.

Reserve Mining Company in 1955, the productivity increases and thus labor savings from pellets became obvious. This led to the significant capital investment in pellet plants which characterized the late 1950s and the mid-1960s. Capital was substituted for labor; thus capital costs per ton molten iron increased, labor costs decreased. The steel industry chose to substitute their second most rapidly increasing cost factor (capital) for their most rapidly increasing cost (labor). It was still an economically rational substitution. It also produced the positive side effect of reducing energy costs per ton molten iron. As experience with pellet burdens grew, capital continued to be substituted for labor savings (and continued to produce savings in the factor which was increasing in cost slowest -- energy) until the 1963 pellet plateau was reached. At this point, productivity stabilized and concomitant labor savings stalled. To stimulate further labor savings, supplemental fuel injection practices were initiated. Thus throughout the latter portion of the 1960s energy and capital were substituted for labor.

Phase III starts with dramatic reversals of previous trends and extends to the present (1977). The reversals can be pin-pointed to 1969 for wage/coke, 1970 for capital/coke, and 1972 for wage/capital. Energy costs soared and energy jumped from the slowest to the fastest increasing cost factor of production. It bumped labor to second place and capital dropped to the slowest factor to increase. These reversals preceded the 1973 Arab Oil Embargo, but the Embargo accentuated phase III trends between 1973 - 1974.*

In phase III, the relative inexpensive status of capital has led the steel industry to expand pellet plant capacity for a third time.

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*Near stabilization of energy prices since 1975 has caused the wage/coke ratio to rebound from the Embargo effects and by 1977 reach a level that is consistent with the phase III pre-Embargo decreasing trend line.

The mid-1970s capital construction of pellet facilities has been the most ambitious to date and is still under way. Energy savings are becoming a major concern for two reasons: One, because energy is the most rapidly increasing marginal productivity cost as Figure 5 illustrates, and two, because of the unreliability of supply of some fuels regardless of price. Natural gas for pellet induration is of particular concern. Supplemental fuel injection at the BF continues and natural gas is one of the injected fuels.

The steel industry presently chooses to substitute capital plus energy for labor. Current substitution ratios indicate the prime savings potential is finding capital substitutions for energy.

4. POLICY IMPLICATIONS OF PELLETS

Introduction

There are a number of policy implications related to the shift to pelletized iron ore. These include: (1) redistribution of employment: (2) redistribution of environmental damage; (3) industrial energy conservation strategies: and (4) mineral taxation by state and federal governments. In all of these cases it is critical to consider the entire molten iron production system rather than divide this system into its customary industrial sectors of iron ore mining and iron and steel production. That is, policy must be followed to the same point of indistinction established by the physical production characteristics of transforming resources into usable products. For pelletized iron ore, therefore, the molten iron production system defines the appropriate boundaries for policy consideration.

With the shift to pelletized iron ore, a portion of the steel manufacturing process was, in effect, transferred from the blast furnace to the iron ore mines. That is, the improved iron ore burden of pellets reduced labor requirements at the blast furnace per ton of molten iron, but required increased labor at the mine. The pellet mill located at the mine site is a physical representation of the relocated manufacturing activity; the increase in mine employment is a direct labor manifestation of this shift in manufacturing.

To a degree some environmental damage has likewise been transferred from blast furnace operations to iron ore mine operations. Pelletized ore burdens reduce blast furnace coke requirements and thus reduce the air and water pollution associated with coke production. The increased energy per ton iron at mines required to produce pellets is an indicator of increased air and water pollution in ore production regions. Further the large volumes of crude ore that must be handled with pelletizing taconite produce substantially increased waste material to be discarded. In some of the taconite ore deposits, trace elements have become of particular concern as pollutants. The case of Reserve Mining Company vs. the State of Minnesota has brought to public attention and legal challenge the problems of asbestos emissions to water and air. The pollution problems are distinctly related to the ores now mined and the expanding manufacturing activities required to make pelletized iron ore. It is interesting that this shift in environmental damage has been away from the areas of large population concentrations near blast furnaces and towards less dense populations associated with the raw materials source regions of the iron ore mines.

Strategies for energy conservation in the iron ore and steel industries must take into consideration the integration of these production systems. Guidelines or regulations that apply only to iron ore or molten iron separately could well produce increased energy consumption, not the desired energy conservation. Pelletized iron ore requires more energy at the mine but should be considered an energy conservation practice when followed to the point of indistinction, the production of molten iron.

Minnesota Iron Ore Taxes

A more detailed look at Minnesota iron ore taxes can illustrate some of the complexities associated with the mineral policies that have been legislated. Minnesota taxes can also illustrate the misconceptions that befall policy development when local vested interests prevail. Parochial policies often promote local interests at the expense of a larger "public good." In such cases, results produced may conflict with initial intentions just as not pursuing the physical point of indistinction can produce conflict between results and intentions in the technical realm.

Initially, Minnesota taxes on iron ore were very low with the purpose of encouraging resources exploitation. The nature of the tax was a production tax and amounted to one cent per gross ton of iron ore mined and shipped. This lenient tax was ruled unconstitutional in 1897 and replaced by an *ad valorem* tax. The *ad valorem* tax was based on 50% of the assessed "full and true value" of mineral properties and thus the tax rates were put in the hands of local assessors. The resulting taxes varied greatly from one mining property to another, and in general were much higher than the earlier production tax rate. In 1907, the State Tax Commission did much to standardize the methods of ascertaining the quantity, quality, and value of natural iron ore on mining properties, but the iron mining industry in Minnesota continued to pay higher taxes than other businesses and industries in the State. This approved policy was rooted in the philosophy that the State should be compensated for the removal of an irreplacable resource and is known as the "natural heritage" theory.

In 1941, the first taconite law was passed in Minnesota. The intention of this law was to levee a very low production tax on taconite in order to encourage the development of the pelletizing process. To make this law constitutional, a minimal *ad valorem* tax was included but it applied only to unmined properties. Thus, as taconite began to be commercially produced in 1955, the rate of taxation per ton of iron was significantly below that of natural iron ore (taconite taxes were 15% of natural ore taxes per ton of iron in 1955: See Table 7). Taconite has enjoyed this favorable tax position until just recently when the tax rate has been increased to a comparable level with natural iron ore. It is interesting to note that just after the superior qualities of iron ore pellets became well known to the industry (1960 and after), a successful attempt was made to hold the line on taconite taxes. Specifically, the 1963 Minnesota constitutional amendment stated that taconite producing companies shall not be singled out for inordinate tax raises and that, for the next twenty five years, taconite taxes would increase only in proportion to increases in State taxes for other manufacturing establishments. It has only been recently, in 1971 and 1975, that taconite taxes have been significantly escalated. Taconite taxes are now on a par with natural iron ore taxes per ton of iron, but even this is somewhat misleading since natural ore taxes have been held nearly constant for the last 20 years. (See Table 7.)

5. FINDINGS AND CONCLUSIONS

Findings

Pelletized iron ore involves an interesting substitution of energy; more energy is consumed in mechanical work to purify the ore at the mine

TABLE 7.

MINNESOTA IRON ORE TAXES

YEAR	TACONITE TAXES: TOTAL		NATURAL ORE TAXES: TOTAL	
	¢/ltp*	¢/ntFe**	¢/ltp*	c/ntFe**
1976	136.4	193	120.†	202
1975	136.8	194	103.1	174
1974	66.7	95	94.7	160
1973	52.7	75	93.6	158
1972	38.7	55	98.4	166
1971	40.3	57	89.2	150
1970	27.1	38	96.6	163
1969	26.3	37	100.8	170
1968	19.2	27	107.0	180
1967	21.5	30	107.5	181
1966	26.3	37	98.8	167
1965	25.2	36	111.9	188
1964	22.4	32	117.3	198
1963	26.8	38	127.7	215
1962	28.6	41	127.2	214
1961	28.2	40	138.8	234
1960	25.3	36	115.7	195
1959	30.3	43	147.7	249
1958	25.2	36	136.5	230
1957	31.5	45	103.2	174
1956	8.3	12	92.6	156
1955	15.9	22	85.1	143
1954	7.2	10	86.4	146
1953	7.8	11	69.3	117
1952	17.7	25	66.0	111

*ltp = long ton of production; ntFe = net ton of iron content

**Iron content of taconite pellets assumed = 63% iron (or 1.4172 conversion ratio; iron content of natural ore assumed = 53% Fe or (1.6846 conversion ratio)

†Estimated.

which in turn reduces the amount of energy consumed in chemical reduction of ore to iron at the blast furnace. The mechanical energy required for pelletization becomes embodied as indirect energy to the blast furnace. When considering the change in all direct and indirect energies (total energy) in the blast furnace as they have changed with the increased use of pelletized iron ore from 1955 to 1975, it has been shown that total energy required/ton molten iron has declined with pellets.

The reduction in energy required to produce molten iron from pellets is remarkable considering that leaner crude ores are mined (and preferred) to produce pellets (20-30% Fe) than to produce natural ore concentrates (30-50% Fe). Part of this energy savings occurs because the lean, taconite ore contains iron and energy. The energy is thermodynamic energy which is released as exothermic heat as pellets are formed. More important, however, is that the physical structure of spherical pellets greatly increases the permeability in blast furnaces. Thus, the chemical reactions of blast furnaces are more efficient. The improved permeability has contributed energy savings more than six times greater than the exothermic heat released in pellet kilns.

The reduced energy requirements of pellets are further remarkable in that pellets allow significant increases in blast furnace productivity, thereby improving overall labor and capital productivity in iron making. Thus the expenditure of more mechanical energy at the mine produces over-compensating reductions in chemical energy requirements at the blast furnace. This new mine product in turn speeded physical production of molten iron which produced net labor savings per ton of product. These savings of labor and energy were accomplished by capital investment in pelletizing plants and net capital per ton molten iron has risen since 1955.

With an all agglomerate burden and no supplemental fuel injection, it is calculated that molten iron would be produced slower but energy savings beyond current practices would amount to more than 4 million Btu/ton of molten iron.

Conclusions

Two conclusions are drawn from these findings. First, input/output that is confined to one industrial sector can be misleading. Changes resulting in associated sectors can more than compensate for analyzed changes within one sector.

Second, piecemeal approaches to industrial energy conservation are inappropriate. Analysis of direct and indirect energies required to produce a potential conservation adjustment must be followed in the industrial process to a point where physical change no longer exists, i.e., the point of indistinction.

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[9] Confirmed by Kenneth C. Allen, Vice President of Administration and Secretary, American Iron and Steel Institute, Washington, D.C., in letter to me of April 12, 1977.

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[12] Calculated from original pellet plant energy inventories. The magnitude of greater energy intensiveness for nonmagnetic ores was confirmed by several Michigan pellet plant operators; most recently in personal communication with major mine engineer on May 12, 1977.

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APPENDIX TABLES

TABLE A-1

ENERGY CONVERSION FACTORS EMPLOYED*

ENERGY SOURCE	Units	Direct: Btu/Unit	Energy Intensity	Total: Btu/Unit
Electricity	Kwh	3,412[1,2]	3.7963[3]	12,953
Natural Gas (Dry)			1.1005[3]	
1975 U.S. Average	c.f.	1,024[4]		1,127
Minnesota Sales, 1975	c.f.	1,001[4]		1,102
Michigan Sales, 1975	c.f.	1,012[4]		1,114
Natural Gas Liquids			1.1544[5]	
LP-gases (Avg.)	Bbl.	4,011,000[6]		4,630,298
Propane	Bbl.	3,843,000[2]		4,436,359
Propane	lb.	21,646[7]		24,988
Coal: Bitum. & Lig.(1975-76)			1.0068[3]	
Production (avg.)	s.t.	23,500,000[6]		23,659,800
Consumption (avg.)	s.t.	22,800,000[6]		22,955,040
Elect. Gen. (avg.)	s.t.	21,630,000[6]		21,777,084
Coal used for coke	s.t.	26,000,000[8]		26,176,800
Petroleum Products			1.2082[3]	
Gasoline; Motor Fuel	Bbl.	5,253,000[7]		6,346,675
Fuel Oil (inc. Diesel)	Bbl.	5,825,000[6,9]		7,037,765
Residual Fuel Oil	Bbl.	6,287,000[6,10]		7,595,953
Lubricants	Bbl.	6,065,000[6]		7,321,733
Production Fuels:			1.27016[12]	
Coke	s.t.	24,800,000[11]		31,500,000[13]
Coke Breeze	s.t.	21,000,000[11]		26,673,360
Blast Furnace Gas	c.f.	95[14]		121
Coke-Oven Gas	c.f.	500[14]		635
Tar and Pitch	Bbl.	6,720,000[11]		8,535,475
Steam	lb.			1,000[13]
MATERIAL SOURCES				
Limestone (minus 4 in.)	s.t.	-0-		240,000[13]
Oxygen	c.f.	-0-		183[13]
Iron ore sinter	s.t.	-0-		2,470,000[13]
Explosives (ammonium nit.)	lb.	-0-		30,000[13]
Bentonite	lb.	-0-		600[13]
Grinding balls, rods, liners	lb.	-0-		17,500[13]
Steel wear parts	1974 $	-0-		47,660[15]
Rubber tires	1974 $	-0-		40,260[15]
Industrial Chemicals	1974 $	-0-		189,700[15]
Clay refractories	1974 $	-0-		114,470[15]
Plant maint. & repairs	1974 $	-0-		32,210[15]
Trade margins	1974 $	-0-		26,390[15]
TRANSPORTATION				
Railroads (unit trains)	s.ton-mi.	250[16]	2.0000[17]	500
Water (lake freighters)	s.ton-mi.	302[16]	2.0823[17]	630

*Numbers in brackets cite footnotes to this table.

FOOTNOTES TO TABLE A-1

[1] Peter Penner and Jaap K. Spek, "Stockpile Optimization: Energy and Versatility Considerations for Strategic and Critical Materials," CAC Document No. 217 (Urbana, Il: University of Illinois), May, 1976, p. 10.

[2] "Nato Pilot Study on the Rational Use of Energy" Draft report of the Committee on the Challenges of a Modern Society, Industrial International Data Base Methodology Group; report prepared for discussion at the Milan meeting, Nov. 8-10, 1976.

[3] Robert A. Herendeen and Clark W. Ballard III, "Energy Cost of Goods and Services, 1963 and 1967," CAC Document No. 140 (Urbana, Il: University of Illinois), Nov. 1974, p. 32: reprinted in Energy Policy, Dec. 1975.

[4] American Gas Association, Gas Facts: 1975 Data (AGA Dept. of Statistics: 1515 Wilson Blvd., Arlington, Va. 22209), 1976, pp. 80 and 205.

[5] An average of energy intensities for natural gas utility products and petroleum refinery products as presented in ref. [3] of this table was used because the stripping of natural gas liquids from wellhead gases requires more work than dry natural gas production but less than petroleum refining. Also, the distribution process for natural gas liquids (e.g., trucks, storage tanks, refilling) is more akin to marketing of petroleum products than natural gas distribution.

[6] Charles Reading, "Annual U.S. Energy Use Up in 1976 - Energy Balance Sheet," Dept. of the Interior News Release (U.S. Bur. of Mines: Washington), March 14, 1976, p. 11.

[7] Irving Snyder, Dow Chemical Company, as reprinted in "Nato Pilot Study..." ref. [2].

[8] Confirmed in conversation with Eugene T. Sheridan, Chief, Branch of Coal Technology and Utilization, Division of Coal (U.S. Bureau of Mines: Washington D.C.), May 3, 1977.

[9] Weighted average of grades 1 to 4 as consumed in 1974.

[10] Weighted average of grades 5 and 6 as consumed in 1974.

[11] National Coal Association Coal Data 1975 Edition (NCA Dept. of Statistics: 1130 17th Street, N.W.: Washington D.C. 20035) 1977, pp. 132-3. Assuming 4% moisture content of coke as consumed and assuming 12% moisture content of coke breeze as consumed.

[12] Calculated using Direct Btu/ton value of coke from ref. [11] and Total Btu/ton value required to produce coke as detailed in process analysis of ref. [13] appendix Table 2 , p. 2 .

[13] Battelle Columbus Laboratories, "Phase 4--Energy Data and Flowsheets, High-Priority Commodities," Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing (BCL, 505 King Ave., Columbus, Oh. 43201, for the U.S. Bureau of Mines), June 27, 1975.

[14] American Iron and Steel Institute, Annual Statistical Report: 1975 (AISI: Washington, D.C.), 1976, p. 73.

[15] Calculated using energy I/O modeling as detailed by Clark Bullard, Peter Penner and David Pilati, "Energy Analysis Handbook," CAC Document No. 214 (Urbana, Il: CAC of University of Illinois), Oct. 1976; corrected for inflation and price margins.

[16] Private communication (March 29, 1977) with Mr. George Anderson, Western Railroad Association, Chicago: ton miles/gal. data compiled by Association of American Railroads and Lake Carriers Assocation (with U.S. Corp. of Engineers); considers unit trains of 200 70-ton cars over significant grade with empty returns and lake freighters using residual fuel oil (#5 or #6).

[17] Peter Penner, "Summary of Transportation Charactertistics for Vehicular Freight Transportation, 1971," CAC Technical Memorandum No. 45 (Urbana, Il: CAC of University of Illinois), Dec. 1975, table p. 3, and private communications with Mr. Penner. Barge energy intensity applied to lake freighters.

TABLE A-2

TOTAL ENERGY CONSUMPTION PER TON OF MOLTEN IRON FROM BLAST FURNACES: 1975, 1965, 1955 +

	millions Btu/unit	1975 Prod.=79.9 $\bar{M}$ntmi		1965 Prod.=88.9 $\bar{M}$ntmi		1955 Prod.=77.8 $\bar{M}$ntmi	
		u/ntmi	$\bar{M}$ Btu/ntmi	u/ntmi	$\bar{M}$ Btu/ntmi	u/ntmi	$\bar{M}$ Btu/ntmi
Natural Ore	1.934/ntFe	.184	.36	.357	.69	.815	1.58
Sinter	6.0/ntFe	.275	1.65	.387	2.32	.172	1.03
Pellets	5.153/ntFe	.541	2.79	.246	1.27	.007	.04
			(4.80)		(4.28)		(2.65)
Fuel Oil	.168/gal	4.74	.80	.60	.10	NR	.00
Tar & Pitch	.203/gal	1.44	.29	-NR-	.00	NR	.00
Natural Gas	1.127/Mcf	.35	.39	.52	.59	NR	.00
B.F. Gas	.121/Mcf	16.73	2.02	*	2.03	*	2.03
Coke-Ov. Gas	.635/Mcf	.15	.10	.13	.08	NR	.00
Oxygen	.183/Mcf	.32	.06	.11	.02	NR	.00
			(3.66)		(2.82)		(2.03)
Coke	31.5/nt	.611	19.25	.656	20.66	.873	27.50
Limestone etc.	.24/nt	.234	.06	.279	.07		.09
			(19.31)		(20.73)		(27.59)
Mill Cinder etc.	0.0/nt	.05	.00	**	.00	**	.00
Scrap	0.0/nt	.05	.00	.04	.00	.05	.00
Refractories	.013/lb	5.0	.06	**	.06	**	.06
Electricity	.013/Kwh	25.0	.33	**	.33	**	.33
Steam	1/1000 lb.	1.2	1.20	**	1.20	**	1.20
			(1.59)		(1.59)		(1.59)
TOTAL	$\bar{M}$ Btu/ntmi		29.36		29.42		33.86
By-Prod. BF Gas	.121/Mcf	48.8	-5.91	*	-5.53	*	-5.53
NET TOTAL	($\bar{M}$ Btu/ntmi)		23.45		23.89		28.33

+ Abbreviations: ntmi = net ton molten iron; NR = not recorded in AISI Annual Statistical Reports and assumed to be zero; * = average BF gas value for 1966 to 1975 AISI record assumed for earlier, unreported years; ** = values held constant at Battelle (1975) levels; see reference [19].

TABLE A-3

TOTAL COST AND RELATIVE COMPONENT COSTS OF MOLTEN IRON PRODUCTION: 1977 PRICES*

Sector	$/long t.	$/net t.	$/ntmi	% Molten Iron Costs by I/O Sector	% Molten Iron Costs for BF Materials Consumption
Iron Ore Pellets [1]					
Pellet Production [2]	13.14				
Capital Amortization [3]	8.75				
Franchise Payments [4]	4.98				
Total Pellet Cost (FOB Mill)	$26.87		$38.07 [15]	24.7	
Mill to Upper Lakes(RR) [6]	3.09				
Stockpile Charge [6]	.05				
Upper Lakes to Lower Lakes(LF) [6]	4.05				
Loading & Unload. [6]	.91				
Total I.O. Transport Cost	$ 8.10		(11.48) [15]		
Total Iron Ore @ BF Cost	(34.97)				32.1
Coking Coal [7]					
High Volatile [8]		22.94			
Medium Volatile [8]		5.30			
Low Volatile [8]		8.95			
Total Coal Cost (FOB mine)		37.21	33.21 [16]	21.5	
Ave. Coal Transport Cost [9]		6.61	(5.90) [16]		
Total Coking Coal @ BF Cost		(44.01)			25.4
Coke Oven Costs					+10.3 35.7
Limestone; Dolomite & other Fluxes:					
Price (FOB mine) [10]		2.07	.48 [17]	0.3	
Transport [10]		2.38	(.56) [17]		
Total Limestone @ BF Cost		(4.45)			0.7
Transport:					
Total wt. ave. cost to BF			17.94	11.6	
Total Major Raw Materials & Transport			(89.70)		-0-†
Blast Furnace Region:					
Coke Price [11]		90.00	(54.99) [18]		
Coke Oven Costs [12]		25.69	(15.88) [19]	10.3	-0-†
BF Operation, other Fuels & Materials [13]			48.70	31.6	31.6
Total Molten Iron Cost [14]			$154.28	100%	100%

*Numbers in brackets cite footnotes to this table.
†Transport costs are disaggregated to materials categories.
**Coke oven costs are relocated into coking coal category.

FOOTNOTES TO TABLE A-3

[1] Based on pellets of 63% Fe content.

[2] Calculated as a residual using total price minus transport, capital, and franchise payment costs.

[3] Calculated from investment of $75/long ton annual capacity at 6% rate of return on initial capital investment and straight line amortization over 25 years.

[4] Based on average rate for Erie, Reserve, and Empire mines as presented in J. K. Hammes, "The Economics of Producing and Delivering Iron Ore Pellets from North American Taconite Type Resources", Mining Symposium, Proceedings of 27th Annual Meeting, Duluth 10-12, 1966 (Minneapolis: U. of Minnesota; 1966), p.11: includes "Royalty; State, provincial and local taxes; and Federal income tax."

[5] Using 55.5¢/iron unit as lower lakes price as published in June 25, 1977, p.18, Skillings Mining Review minus transportation costs as published in Jan. 8, 1977, p.44, Skillings Mining Review.

[6] "Rail and Lake Freight Rates on Iron Ore and Pellets per Gross Ton", Skillings Mining Review, (Jan. 8, 1977), p. 44.

[7] Based on blend rate of 20% low, 14% medium, and 66% high volatile Northern Appalachian coking coals per conversation with Mr. Eugene Sheridan, Director of Coal Office, U.S. Bureau of Mines, May 3, 1977, and data published in Minerals Yearbook, "Coke and Coal Chemicals".

[8] World Scan: Coal Week (McGraw Hill Publishers) May 30, 1977, using average of spot and term prices.

[9] Ibid., using various modes of transport and representative origins and destinations.

[10] Prices supplied by superintendent of limestone mine owned by major steel company, July 22, 1977.

[11] World Scan: Coal Week (McGraw Hill Publishers) May 30, 1977, "international spot price, fob coke oven."

[12] Coke price/ntmi less delivered coking coal price/n.t. adjusted for 68.43% coke yield (1975) from coking coal blend according to Eugene Sheridan, "Supply and Demand of United States Coking Coals and Metallurgical Coke", Bureau of Mines Special Publication, (Washington, D.C.: U.S. BOM, 1976, p.15)

[13] Calculated as a residual from molten iron composite price minus all preceding costs. Includes ore yard, sinter strand, mill scale, and scrap to blast furnace, and blast furnace operations.

[14] Published "composite price; based on average prices for basic and foundry pig iron at representative producing points within the U.S. (as appearing regularly in Iron Age, magazine): annual averages from 1967 to 1972 were found to correspond closely to price deflators for primary iron and steel industry (CAC Tech. Doc. #214), but diverge widely after 1972 with more than a doubling in price during 1974 ($78.16 to $172.79) and then no price change since Feb., 1975, (stable at $187.67 to July, 1977). Current "composite price" for molten iron could not be used therefore. Average 1972 published composite price ($79.70) provided the base and was increased by the percent increase in price deflators for I/O industrial class #3701-04 to 1974 (CAC Tech. Doc. #214) and then to 1977 by repeating 1974 to 1975 change in price deflator for manufacturing (14%/yr.), the most recent published in Survey of Current Business ("Implicit Price Deflators and Price Indexes," July, 1976, table 7.5, p. 59). Resulting 1977 molten iron price was verified by industrial experts as reliable.

[15] Converted according to 1411.2 lb. Fe/long ton pellets of 63% Fe and 2000 lb. Fe ore/net ton molten iron, yield ratio of 1.417 of l.t. pellets to ntmi. Normal iron ore burden rates are 97.5% (or 1950 lb./ntmi), but 2000 lb. is used to allow for pellet breakdown in transport loss, slag loss, breeze loss, and other losses of Fe.

[16] Converted according to 1.461 tons coking coal per ton coke (see Sheridan, as cited in footnote #12) times .611 net tons coke/ ntmi (American Iron and Steel Institute, Annual Statistical Report: 1975, Washington, D.C.: AISI, 1976), yields ratio of .893 net ton coking coals/ntmi.

[17] Limestone ratio of .234 net ton/ntmi used as published in American Iron and Steel, Annual Statistical Report: 1975, (Washington, D.C.: AISI), 1976, p.63. Includes "limestone, dolomite, and other flux materials" as changed directly into blast furnaces plus tonnage consumed in the production of self fluxing agglomerates.

[18] Converted according to .611 n.t. coke/ntmi as cited in footnote #16.

[19] Coke price/ntmi less price of delivered coking coal/ntmi.

NOTE: Total cost schedule was reviewed by industrial experts and verified as reliable.

TABLE A-4

SECTOR COSTS OF MOLTEN IRON PRODUCTION SEPARATED INTO LABOR, CAPITAL AND INPUT COMPONENTS+

Industrial Sector	% of total molten iron costs*	LABOR			CAPITAL			INPUTS		
		Ratio to total output **	% of total m.i. costs	% of direct m.i. labor costs	Ratio to total output **	% of total m.i. costs	% of direct m.i. Capital costs	Ratio to total output **	% of total m.i. costs	% of m.i. input costs
IRON ORE (fob mine)	24.7	.19	4.69	16.2	.26	6.42	32.1	.56	13.83	26.8
COAL (fob mine)	21.5	.35	7.53	26.1	.24	5.16	25.8	.42	8.94	17.4
LIMESTONE (fob mine)	0.3	.29	0.09	0.3	.27	0.08	0.4	.45	0.13	0.3
TRANSPORT (major raw materials)	11.6	.42	4.87	16.9	.19	2.20	11.0	.39	4.54	8.8
BLAST FURNACE OPERATIONS	41.9	.28	11.73	40.6	.15	6.16	30.8	.58	24.54	46.8
TOTAL (for molten iron prod.)	100.0%	-	28.91	100%	-	20.02	100%	-	51.98	100%

+ Imports are assumed to have same component characteristics as U.S. production.

* From Table A-3.

** Total Output Ratios from Albert Walderhaug, "The Composition of Value Added in the 1963 Input-Output Study," Survey of Current Business (April 1973), Table 1, p.36.

TABLE A-5

ANNUAL FACTOR COSTS USED FOR SUBSTITUTION INDEX RATIOS

Year	Coke(1)	Wages(2)	Capital(3)
1977	$ 65.75*	$ 12.71**	8.21†
76	64.70*	11.74	8.39
1975	64.55	10.59	9.25
74	53.28	9.08	9.43
73	26.75	7.68	8.05
72	22.81	7.08	7.53
71	20.30	6.26	7.75
1970	17.70	5.68	7.83
69	15.01	5.38	6.48
68	14.33	5.03	5.91
67	14.37	4.76	5.25
66	13.94	4.63	4.88
1965	13.51	4.48	4.43
64	13.29	4.36	4.39
63	13.62	4.25	4.28
62	14.14	4.16	4.16
61	14.00	3.99	4.28
1960	14.03	3.82	4.23
59	14.02	3.80	4.11
58	14.15	3.51	3.72
57	14.08	3.22	3.91
56	13.28	2.95	3.15
1955	12.60	2.72	3.03
54	12.89	2.51	3.00
53	13.17	2.44	3.12
52	13.14	2.32	3.03
51	12.70	2.11	2.90
1950	12.30	1.91	2.80
49	12.18	1.75	2.83
48	11.58	1.68	2.83
47	9.60	1.56	2.76
46	8.17	1.40	2.78
1945	7.45	1.31	2.83
44	7.16	1.28	2.95
43	6.70	1.19	2.97
42	6.18	1.11	3.01
41	5.53	1.01	2.99
1940	5.25	0.91	3.01

(1) COKE = "Cost (value) of coal per ton of coke" as published by the Bureau of Mines in Minerals Yearbooks, "Coke and Coal Chemicals" Chapter.
*Calculated from Coal Week - World Scan (McGraw-Hill Pub. Co.)

(2) WAGES= "Average total payroll cost per hour for employees receiving wages" as published by the American Iron and Steel Association in their Annual Statistical Reports.
**1977 wages represents average for first six months as reported by AISI Statistics Dept. by telephone on September 14, 1977.

(3) CAPITAL = Long-term interest rates on major steel company AA bonds as calculated from The Commercial and Financial Chronicle, for the N.Y. Stock Exchange Bond Market. All AA bonds for the seven largest U.S. steel companies were followed. Annual average is composite of annual market values (current yields) for bonds with 20 or more years to maturity for years 1953 through 1976; for bonds with 15 or more years to maturity for years 1940 to 1952.
†July 19, 1977 current yields used.

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